MORPHOLOGY, PALEOGEOGRAPHIC SETTING, AND ORIGIN

OF THE MIDDLE WILCOX YOAKUM CANYON,

TEXAS COASTAL PLAIN

APPROVED:

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MORPHOLOGY, PALEOGEOGRAPHIC SETTING, AND ORIGIN OF THE MIDDLE WILCOX YOAKUM CANYON, TEXAS COASTAL PLAIN

By

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF ARTS

THE UNIVERSITY OF TEXAS AT AUSTIN

December, 1987

ACKNOWLEDGEMENTS

I wish to extend my thanks to my advisor, Dr. William E. Galloway, for his support of this project. He always made time to hear of my newest dilemma and always provided the necessary help, whether a timely suggestion or a kick in the pants. My committe members provided additional help. Dr. Amos Salvador has kept me in a general good humor and has provided invaluable advice throughout my time at the University of Texas. And, in spite of Dr. John G. Sclater's failure to improve my golf game, he was integral in the development of the decompaction program used in this study.

I owe a great deal of thanks to the National Science Foundation, Union Oil Company of California, and the Gulf Coast Association of Geological Societies for the financial support they provided for this study.

And, finally, I would like to thank my parents, without whom I would never have successfully gotten into graduate school, and the rest of my family, especially my sister Anne and her family, without whom I would have never gotten <u>out</u> of graduate school.

This thesis was submitted to committee in August, 1987.

William F. Dingus

The University of Texas at Austin

December, 1987

ABSTRACT

The Yoakum Canyon is the largest of the Gulf Coast Eocene erosional gorges and is interpreted as a buried submarine channel. It can be traced for 67 miles from the Wilcox fault zone, which defines the position of the early Eocene shelf edge, nearly to present outcrop. This paper expands on previously published descriptions of the canyon using a more extensive subsurface data base. Decompaction of the canyon shale-fill reveals that original depths of the canyon exceeded 3500 ft (1067 m). Apparent canyon wall slump scarps and a peripheral chaotic zone, interpreted as an incipient slump feature, are comparable to similar features of the late Quaternary Mississippi submarine canyon.

The Yoakum canyon formed within the Garwood subembayment to the west of and adjacent to the Middle Wilcox continuation of the Rockdale delta system. Quantitative mapping of facies adjacent to the Yoakum shale indicate the following sequence of events: 1) Muddy, distal deltaic and shelf facies of the lower Middle Wilcox were deposited during a retrogradation. 2) A resurgence of progradation deposited the upper Middle Wilcox deltaic sands atop the unconsolidated, lower Middle Wilcox continental margin muds creating a density inversion which initiated slump failure of the continental margin sediments. 3) Headward erosion of the canyon across the shelf occurred contemporaneously with a subsidence-induced transgression caused by a decrease in the sediment supply. The Yoakum canyon was excavated by a combination of slumping and current scour. 4) The canyon was filled with hemipelagic and prodelta muds. 5) Progradation of the Upper Wilcox (Carrizo) deltaic sands capped the sequence.

TABLE OF CONTENTS

LIST OF FIGURES

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INTRODUCTION

Statement of Problem

Several large, gorge-like features were incised into the deltaic, progradational sedimentary wedges of the Texas gulf coast (Hoyt, 1959, Chuber and Begeman, 1982, Winker, 1982, McCulloh and Eversull, 1986). One of the largest of these was the Yoakum canyon (Fig. 1). Its morphology and paleogeographic position indicate it was originally a submarine canyon. It was a large feature with widths exceeding 10 mi (16 km), depths of greater than 3500 ft (1067 m) and a length of more than 60 mi (96 km).

The origin of submarine canyons excavated within an otherwise progradational depositional environment is controversial. Two major, conflicting theories prevail regarding the formation of such large, erosional features within a progradational cycle. One theory maintains that in order to create a feature like the Yoakum canyon sea level must be lowered to at or below the shelf-edge so that sub-aerial, fluvial erosion can initiate canyon formation (Vail et al., 1977). Another theory calls for the rise of sea level and sediment starvation of the shelf-edge to initiate canyon formation (Brown and Fisher, 1980). While both theories have merit, only one will apply to a given situation. This paper proposes a variation of the latter model as an explanation for the genesis of the Yoakum submarine canyon.

Location

The Yoakum Canyon is located within the Wilcox progradational wedge which built out into the Gulf of Mexico during late Paleocene and early Eocene time

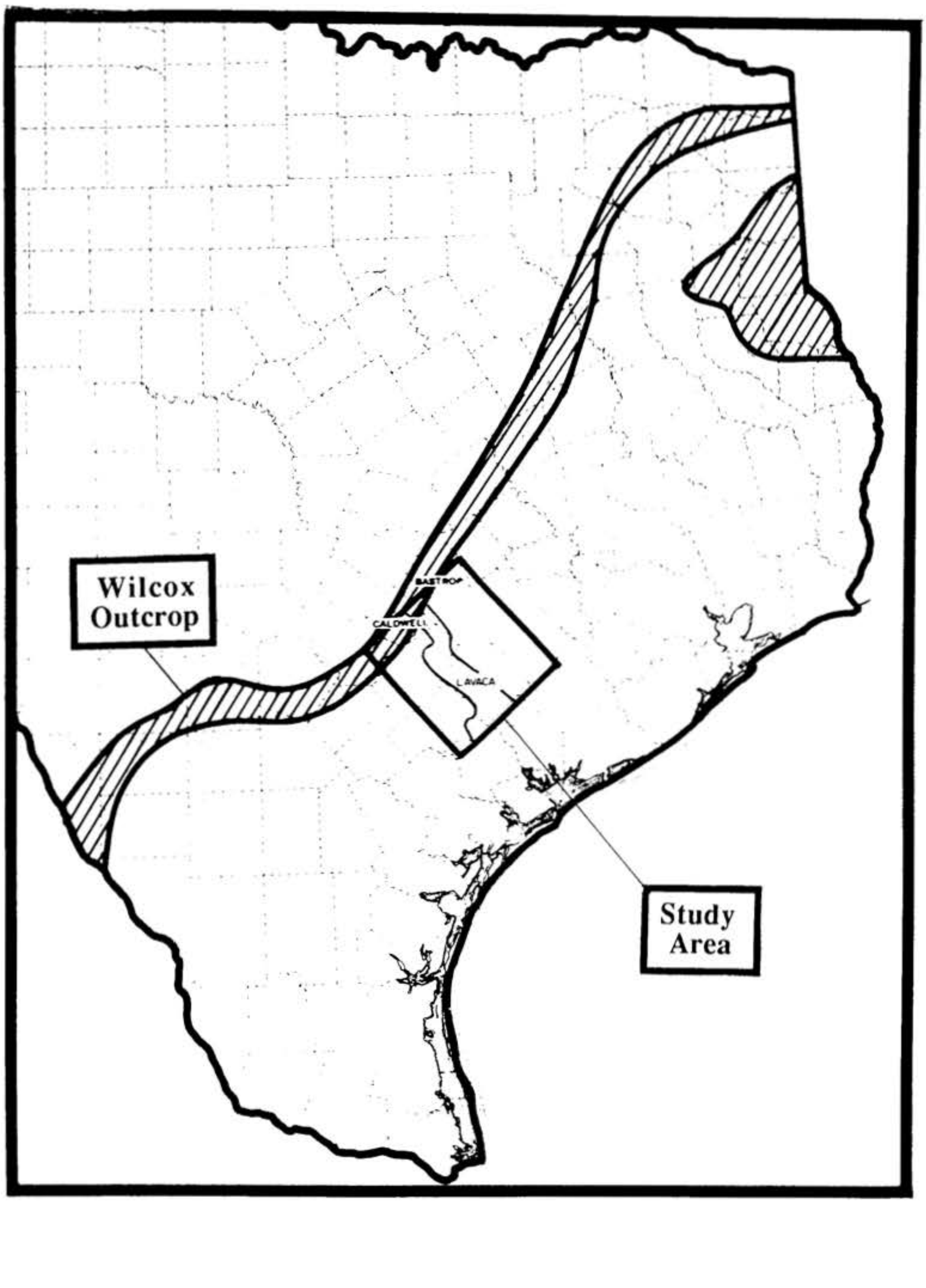


Figure 1: Location map of the study area showing the margins of the Yoakum canyon and the area of Wilcox outcrop. Note that Lavaca County is the only county located entirely within the study area.

(Galloway, in press, Fig. 2). Well data show the canyon is filled with shale. The canyon itself does not crop out but intervals stratigraphically equivalent to the Yoakum canyon-fill do crop out in Caldwell and Bastrop counties. The canyon trends northwest-southeast from the shallow subsurface near the Wilcox outcrop to the approximate position of the paleoshelf-edge (Winker, 1982; Figs. 1 and 3). The mouth of the feature is poorly documented due to the paucity of subsurface data, a function of the extreme burial depth (>10,000 ft, 3000 m) of the downdip section.

The Yoakum canyon is situated, both geographically and stratigraphically, between two large delta systems (Fisher and McGowen, 1967, Edwards, 1982). Unlike modern Texas Gulf Coast deltas these delta systems were of a comparable scale to the modern Mississippi delta. The direction and timing of sediment input suggests that the sediments comprising these delta complexes were derived from the Laramide uplifts to the northwest (Winker, 1982, Ayers, et al., 1985).

The Lower Wilcox Rockdale delta, the older of the two, had a depocenter located in the Houston Embayment, northeast of the position of the Yoakum canyon. The Rockdale delta system became active during the late Paleocene and was the site of deposition for 80 percent (by volume) of the known Lower Wilcox sediments (Fisher and McGowen, 1967). Although the Rockdale delta was most active during Lower Wilcox time it remained active through Middle Wilcox time (Ayers and Lewis, 1985).

To the southwest of and stratigraphically higher than the Yoakum canyon was the Rosita delta system. During late Middle Wilcox time an avulsion of the primary river feeding the Rockdale delta diverted sediment to the newly dominant Rosita delta system (Winker, 1982, Ayers et al., 1985). The Rosita delta system was the depocenter for the Upper Wilcox sediments which eventually prograded out over the Yoakum canyon and arrested its formation.

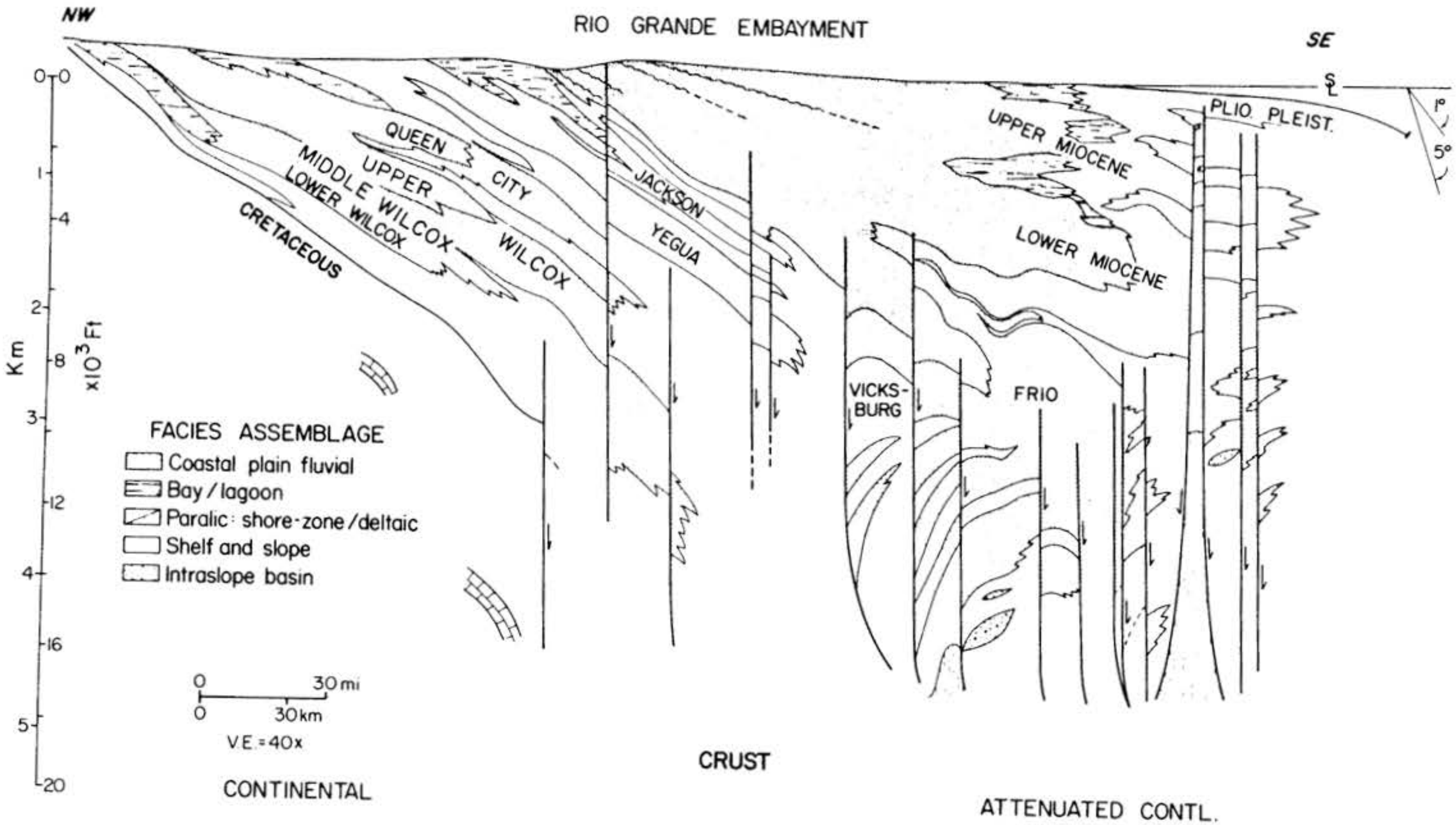


Figure 2: Generalized Gulf Coast cross-section (modified from Galloway, in press).

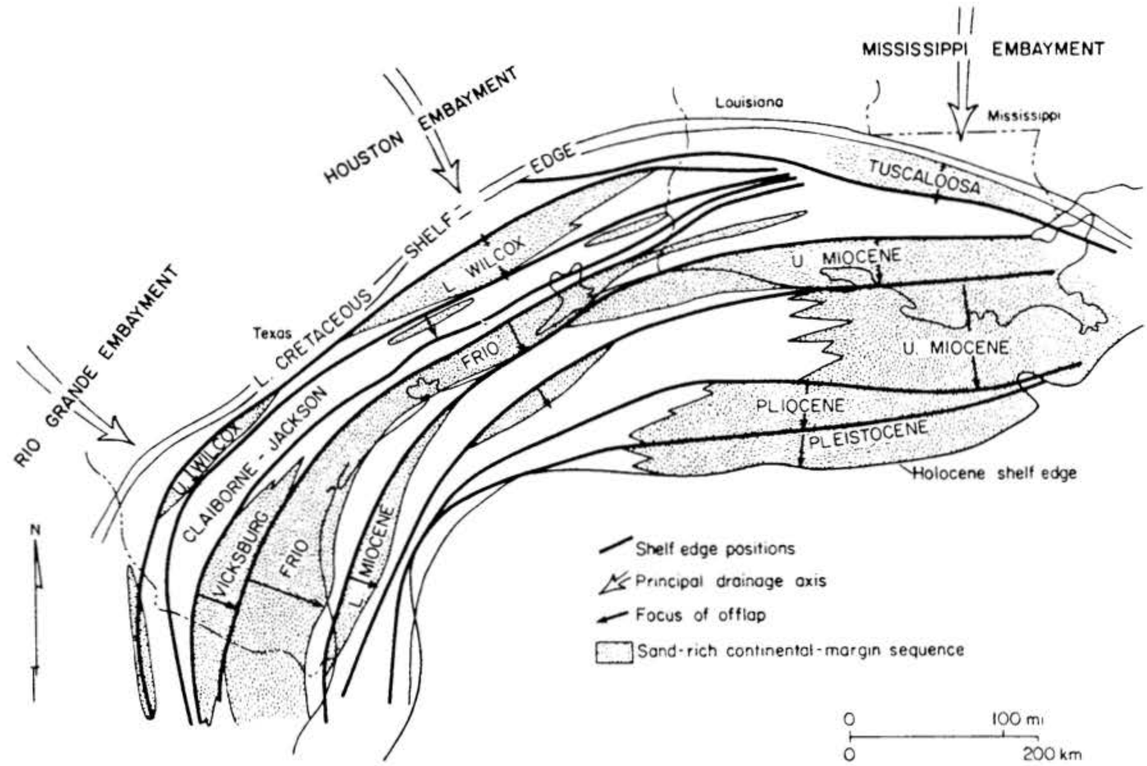


Figure 3: Shelf edge positions through time for the Texas and Lousiana Gulf Coast (modified from Winker, 1982).

Previous Work

The Yoakum canyon was first described by Hoyt in 1959. He recognized it as an erosional channel and proposed factors which may have led to its formation including fluvial erosion, the instability of the Wilcox sediments, and mass wasting via slumping. The expansion of the data base during the 28 years since Hoyt's original study makes possible this more detailed study of the Yoakum canyon. Hoyt had at his disposal the data from only 38 wells located within the boundaries of the canyon. This study makes use of over 650 well logs, 130 of which are within the confines of the canyon margins. Additionally, four seismic lines (three across the canyon and one parallel to a portion of the northeastern flank - all in the downdip region, all proprietary (Fig. 7)) - field inspection of related outcrop, and well cuttings were used to delineate and describe the canyon-fill and equivalent strata.

Little work subsequent to Hoyt's publication has further described the Yoakum canyon. Chuber, (preprint) proposed that the walls of the canyon were terraced. His study area, however, was small (11 mi^2 (29 km^2)) and maps generated as part of the present study indicate terracing is not a dominant feature within the canyon as a whole. Vormelker (1979), in an effort to determine an approximate volume for the resultant fan, estimated the volume of sediments exhumed during the formation of the canyon to be 74 mi^3 (310 km^3). For this he used Hoyt's original map without alteration. No other examinations of the Yoakum canyon have been published.

Significance and Scale of Canyon

The Yoakum canyon was of approximately the same dimensions as the modern Grand Canyon of Arizona (Fig. 4). Determining the factors which lead to the formation of such a huge erosional feature within an otherwise depositional setting is necessary for a complete understanding of the processes involved during passive continental margin progradation. Intense hydrocarbon exploration has provided a wealth of data for the detailed study of the Yoakum canyon. Thus, the Yoakum canyon provides a unique natural laboratory for the study of submarine canyon genesis.

MORPHOLOGY AND FILL OF CANYON

Lithology of Canyon-Fill

Electric log patterns and well cuttings indicate the Yoakum canyon is filled with a homogeneous, highly glauconitic, gray-green shale with isolated pockets of sand (Fig. 5). The Yoakum canyon shale-fill was first penetrated in 1945 when the Pure Oil Company drilled a well, the #1 Vick (Fig. 7), while attempting an eastward extension of the recently discovered Yoakum gas field. Instead of normal Wilcox sands the #1 Vick penetrated an unexpected section of shale 1585 feet (483 m) thick. Further drilling confirmed the presence of this anomalous shale and the feature was dubbed a "shale bank" for lack of a more descriptive term (Hoyt, 1959).

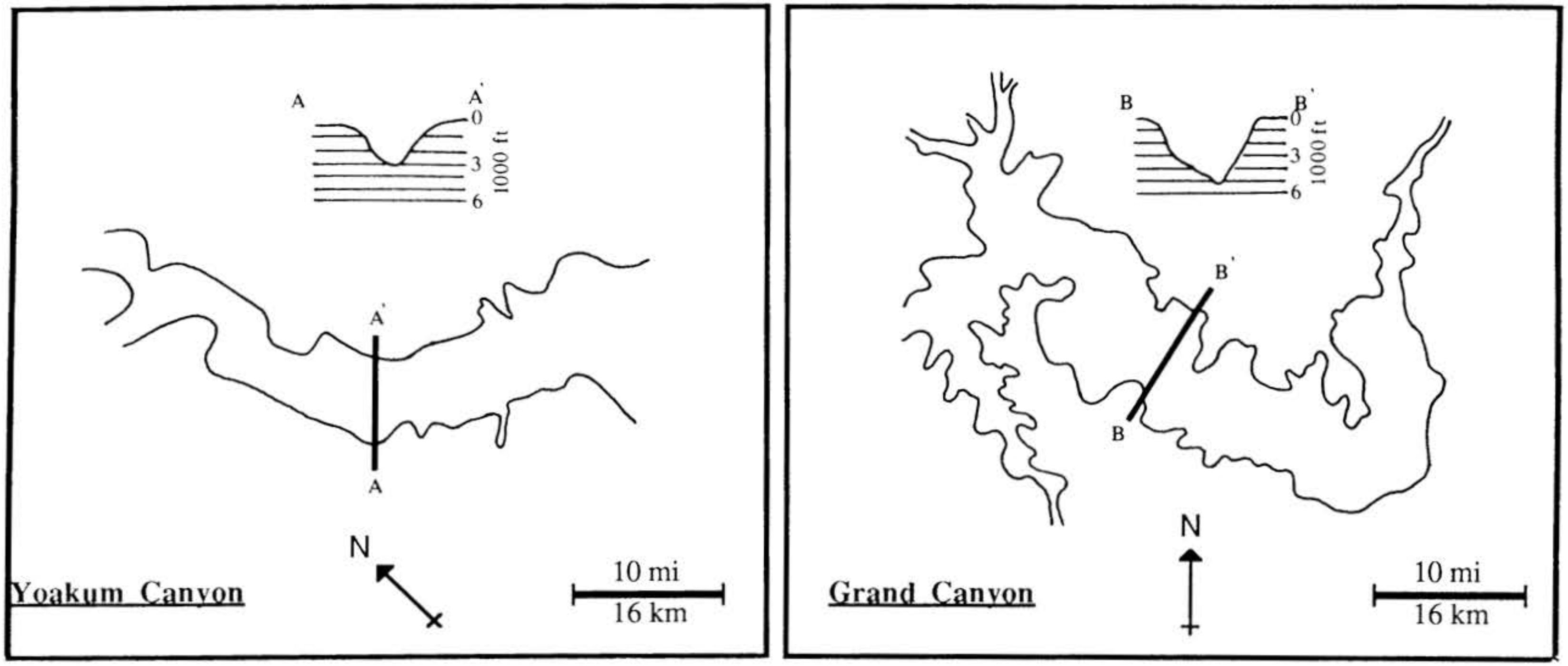


Figure 4: Size comparison of the Yoakum Canyon and the Grand Canyon (modified from Hunt, 1974, and Huntoon, 1974).

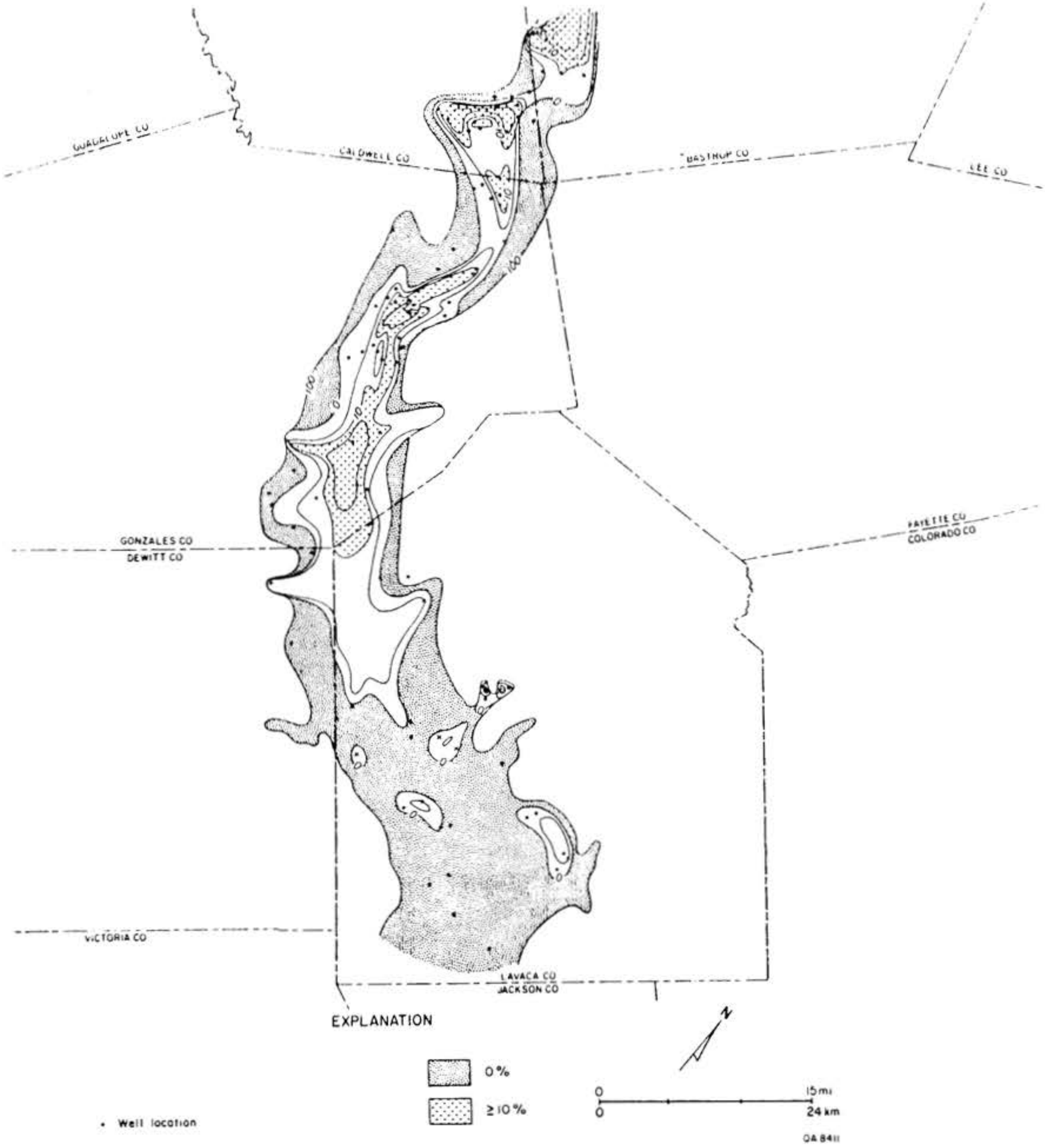


Figure 5: Percent sand within the Yoakum canyon-fill.

Isopach of Canyon-fill

In 1959 Hoyt constructed an isopachous map of this "shale bank" and discovered that it had a gorge-like morphology (Fig. 6). He maintained that the "continuity of sedimentation" across the feature was clear evidence for an erosional origin. Hoyt referred to the feature as the Middle Wilcox Channel, but it is now commonly called the Yoakum canyon.

The simplest way to map the morphology of the canyon is, as Hoyt did, by contouring the thickness of the canyon shale-fill. An isopachous map of the Yoakum shale-fill similar to that of Hoyt was generated as a part of this study (Fig. 7). It reveals the dimensions and morphology of the shale wedge which now defines the Yoakum canyon. This is not to say that it represents a true picture of the dimensions and morphology of the Yoakum canyon at the time of its maximum excavation. In order to best approximate the size, shape, and gradient of the canyon prior to its burial it is necessary to decompact the shales which fill it (Edmondson, 1984).

Decompaction of Canyon-fill

Decompaction removes the compression of muddy sediments which occurs with increasing depth of burial. Since compaction of sediments occurs in the vertical direction, with little horizontal distortion, the areal expression of the Yoakum canyon will not change significantly upon decompaction. However, thickness of the shale-fill and, thus, apparent depth of the canyon will increase. In other words an

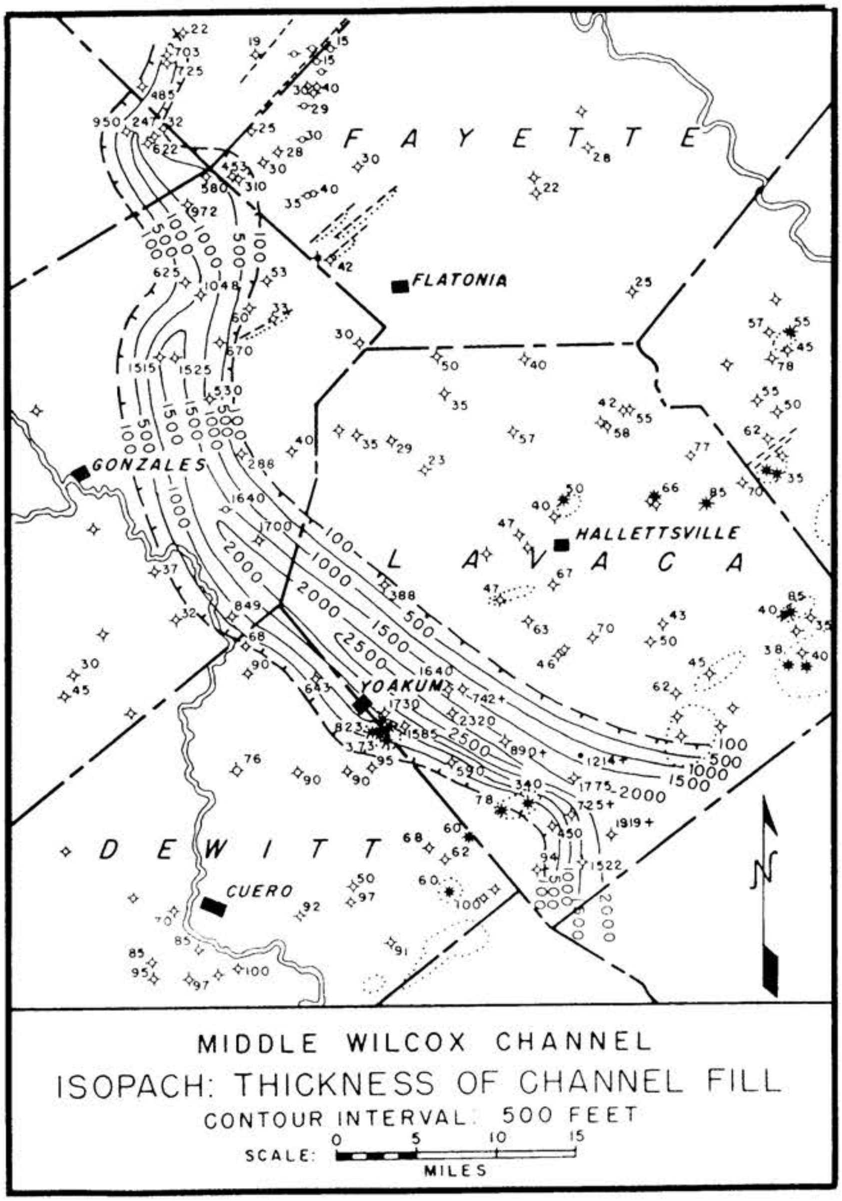


Figure 6: Hoyt's isopachous map of the Yoakum canyon-fill (from Hoyt, 1959).

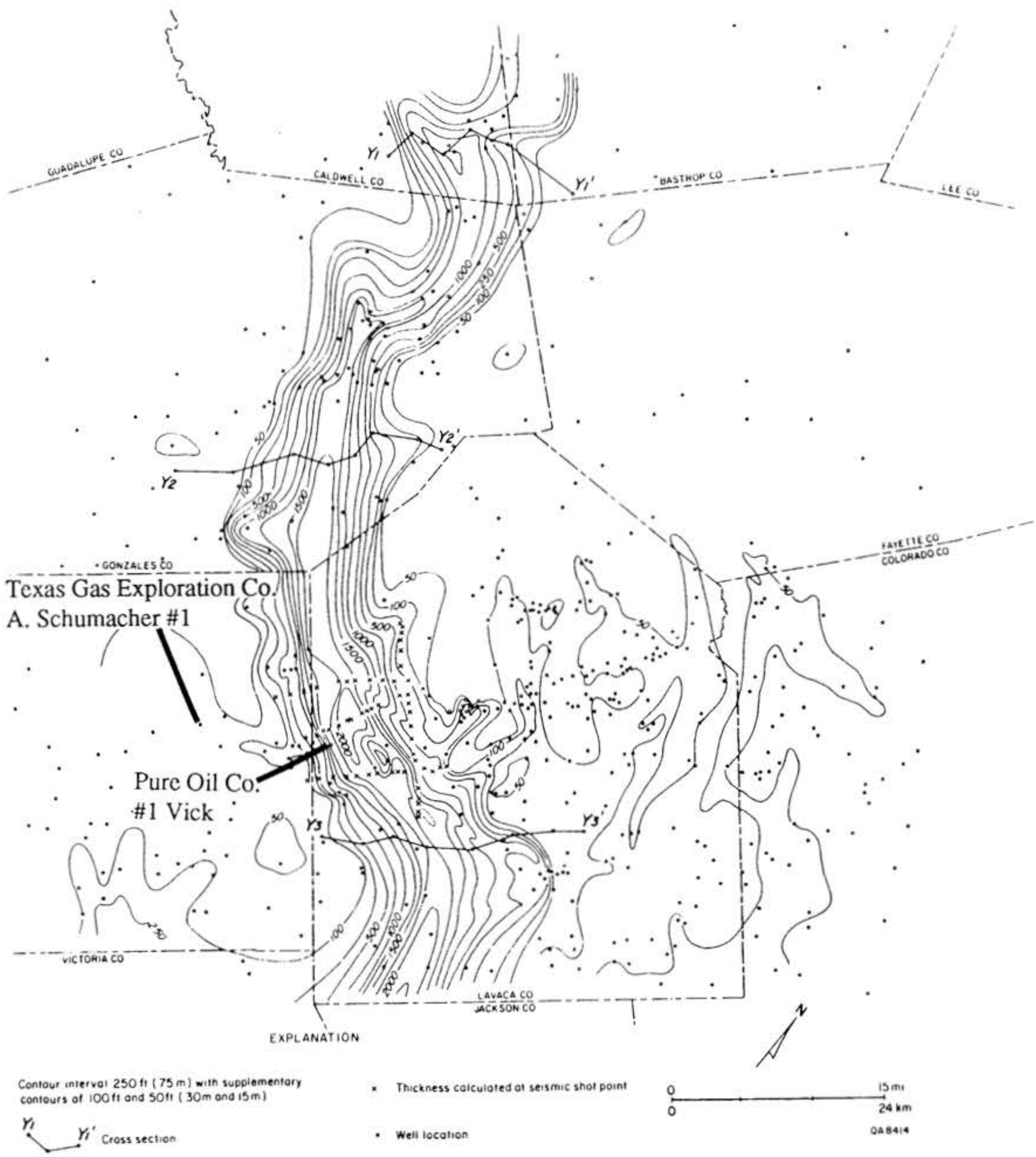


Figure 7: Isopachous map of the Yoakum canyon-fill and equivalent Yoakum shale.

approximation of the Yoakum canyon using the isopachous map of the shale-fill will lead to an interpretation of an original depth of the channel which is erroneously shallow unless compaction is considered. Additionally, the greater amount of compaction which has occurred in the downdip, more deeply buried portion of the canyon reduces the apparent canyon gradient.

Decompaction of the Yoakum canyon-fill involves the assumption that the canyon was completely filled with silts and muds prior to further burial by Upper Wilcox sands. Figures 23 and 24, to be discussed later, show net sand and percent sand maps of the Upper Wilcox section, which directly overlies the Yoakum Shale. The trend of the canyon is reflected in the net sand map (Fig. 22) as a thick belt of sand. This is due to the greater amount of space available for sediment accumulation above the compactable canyon muds. The percent sand map of the same section (Fig. 23) , however, shows no noticeable reflection of the canyon trend. If the canyon had existed as a bathymetric feature at the onset of deposition of Upper Wilcox deltaic sands it would have influenced their depositional trend and be reflected in the percent sand contour pattern. Thus, I conclude that the canyon was filled prior to the deposition of the Upper Wilcox sands. (For a complete description of the decompaction process as well as a listing of the actual computer program see Appendix I.)

The isopach map of the decompacted values of the canyon shale-fill represents the best approximation of the original morphology of the Yoakum canyon at the time of its maximum excavation (Fig. 8). Comparison of this map to the isopachous map of the Yoakum shale-fill (Fig. 7) shows the canyon margin geometry remains essentially unchanged. Apparent canyon depth, as expected, increases with decompaction. The original Yoakum shale-fill isopach never exceeds 2500 feet (762

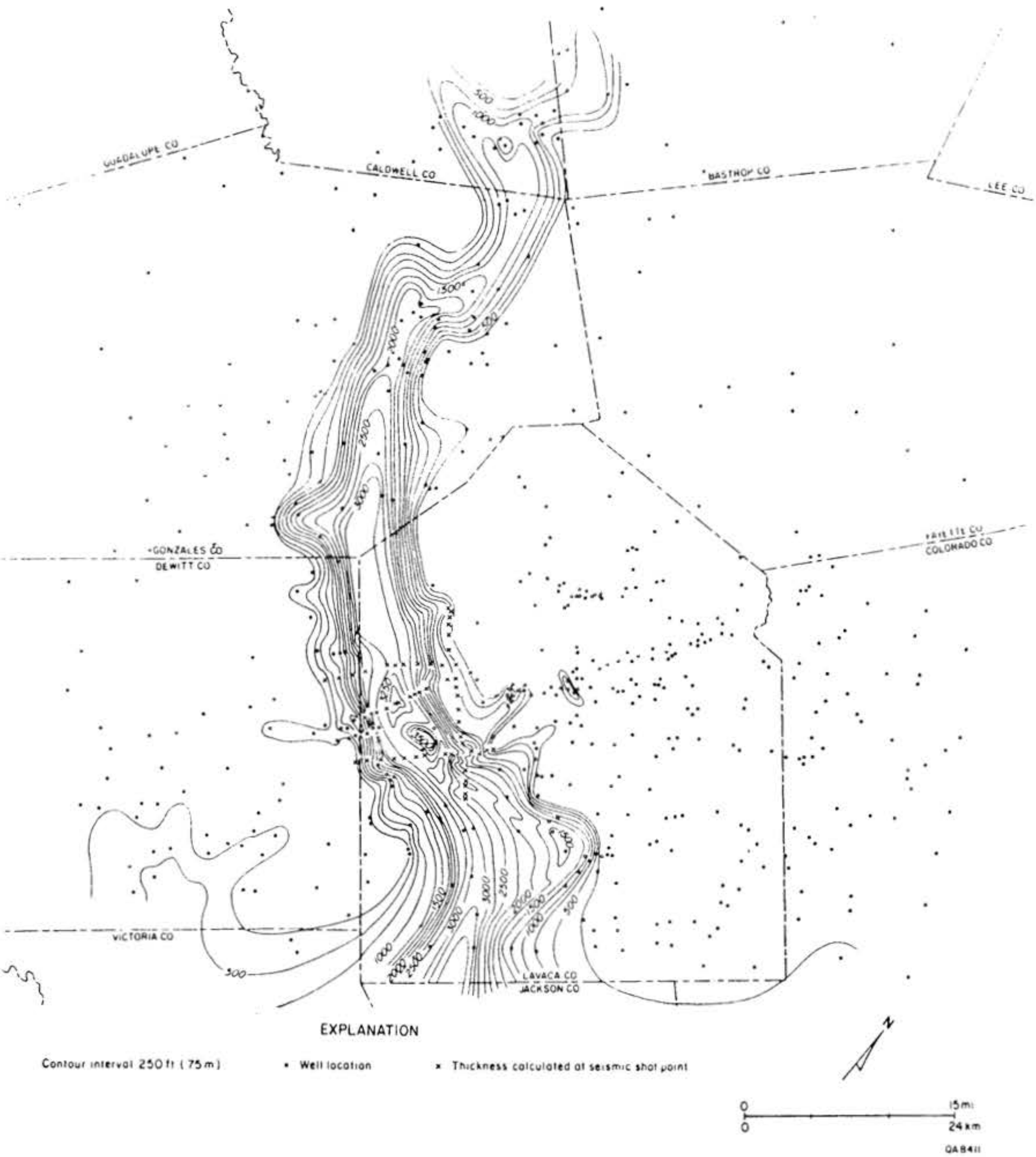


Figure 8: Isopachous map of the decompacted Yoakum canyon-fill.

m) in thickness. The decompacted map demonstrates thicknesses, and paleodepths, which exceed 3500 feet (1067 m).

The computer program which generated the 3-dimensional representation of the canyon (Fig. 9) calculated its volume to be 80 mi^3 (333 km^3). This figure is surprisingly close to Vormelker's estimation of 74 mi^3 (310 km^3) which was obtained by approximating the Yoakum canyon as a longitudinally bisected cone and, in effect, performing a simple decompaction of the canyon shale-fill.

Overview of Yoakum Canyon

The Yoakum Canyon can be traced from near Wilcox outcrop for 67 mi (108 km) to near the paleoshelf-edge (where burial depths are great and subsurface data do not exist). The actual length of the canyon may have been in excess of 80 mi (129 km) with a proportional increase in volume. Maximum canyon depth exceeded 3500 ft (1067 m) and widths varied from as little as 4 mi (7 km) in the updip section to 12 mi (20 km) near the canyon mouth. Width to depth ratios of the canyon averaged approximately 40:1. Overall gradient within the canyon was approximately 0.5° but local reverse gradients exceeded 2°. (Shelf gradient is assumed to have been equivalent to modern shelf gradients of the Gulf of Mexico, approximately 0.1°). The canyon was U-shaped in cross-sectional profile, becoming V-shaped downdip. Canyon walls sloped up to 11° from the horizontal. A series of vertical indentations scalloped the canyon walls. The path of the proposed channel thalweg was slightly sinuous and occasionally bifurcated (Fig. 10). The contours suggest there existed tributary canyons at the updip limit of the data. At its downdip limit the canyon

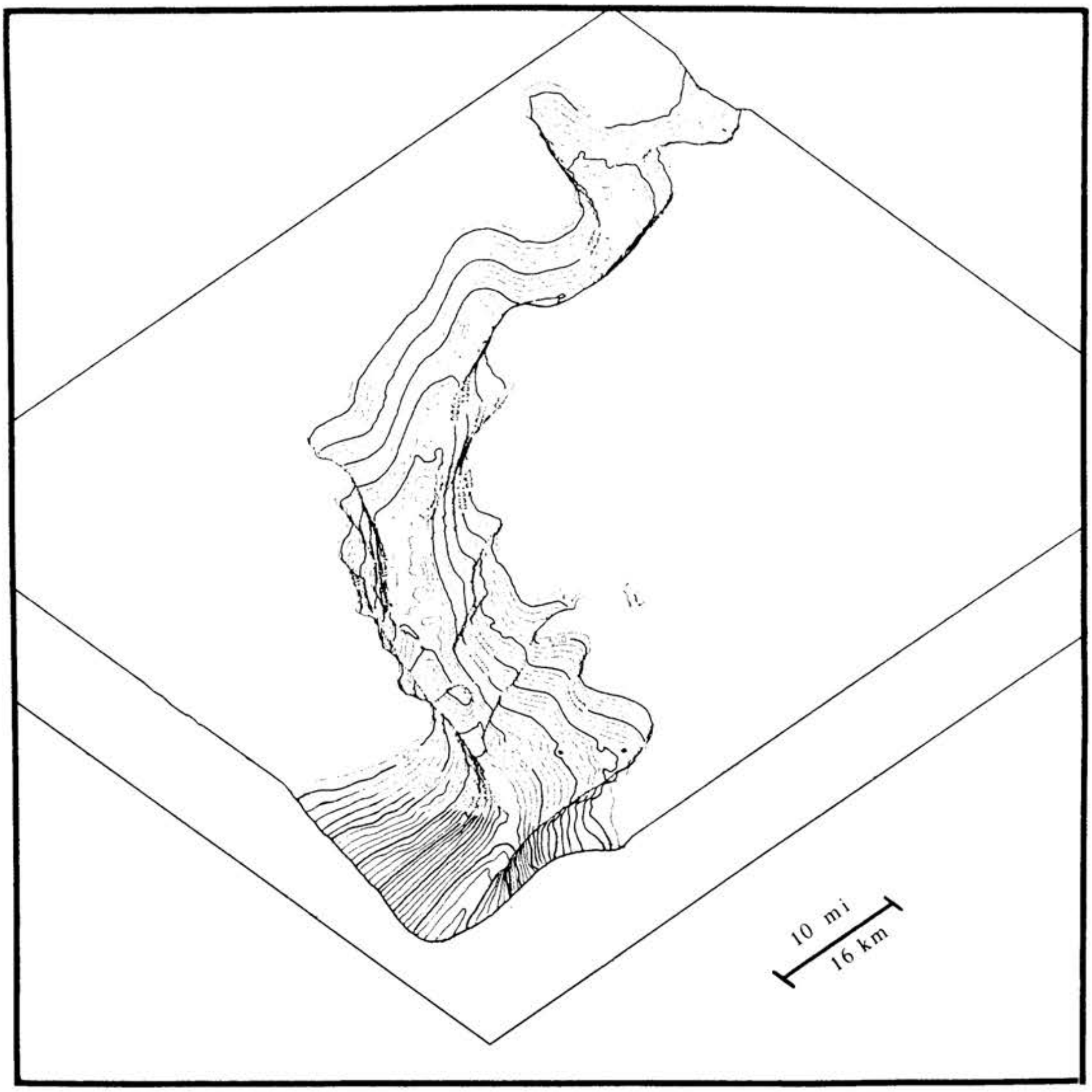


Figure 9: Three-dimensional representation of the decompacted Yoakum canyon shale-fill showing the best approximation of the original morphology of the Yoakum canyon at the time of its maximum excavation. This figure was generated using the Radian Corporation's CPS-1 contouring program. The same program was used to calculate the volume of the canyon as 80 mi^3 (333 km^3). Vertical exaggeration is approximately 40:1.

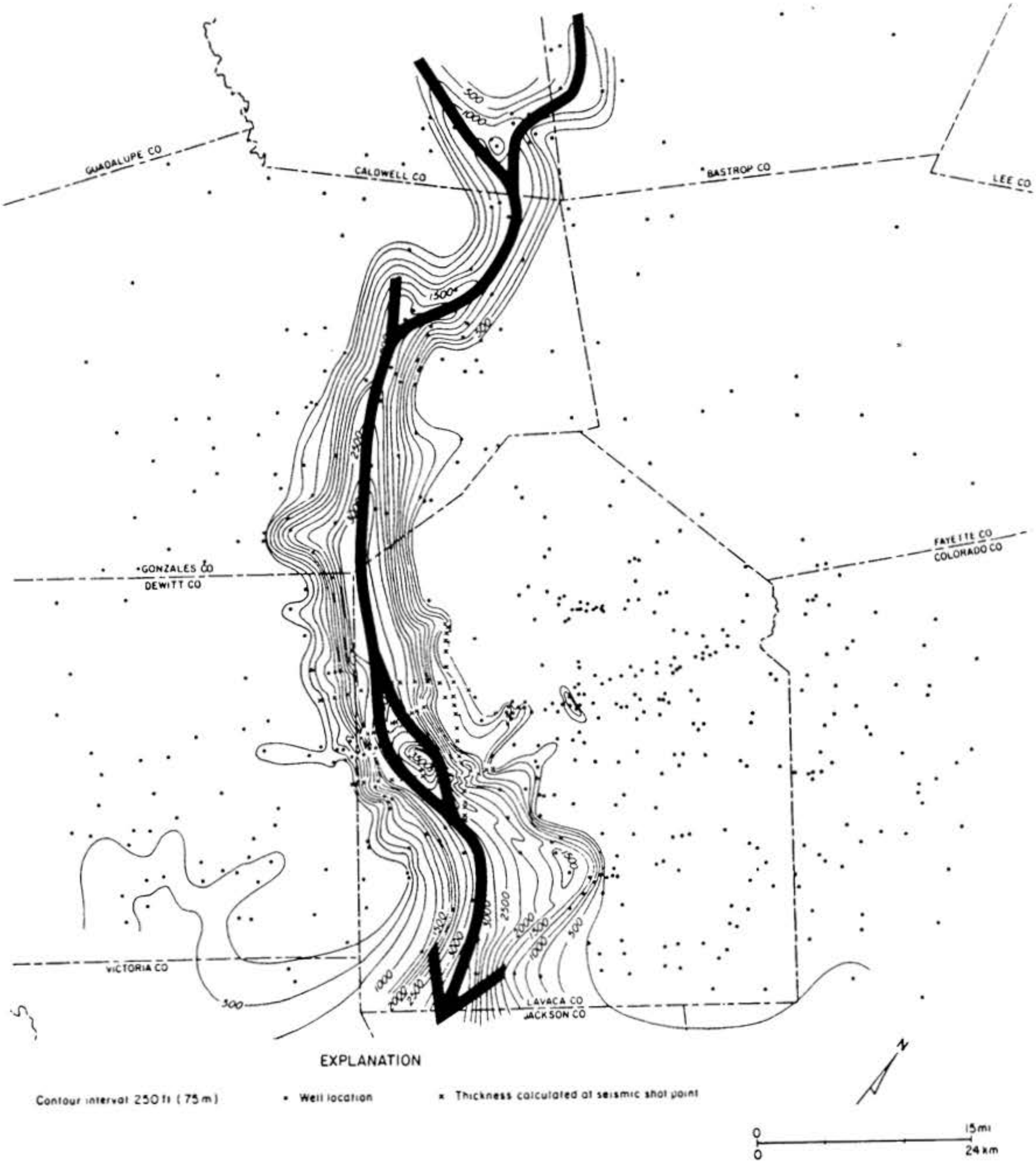


Figure 10: Apparent thalweg of the Yoakum canyon at the time of its maximum excavation. Note coalescence of updip tributaries and bifurcation of thalweg around the positive mound on the canyon floor.

margins flair indicating the proximity of the shelf-edge. The reentrants of the 250 ft and 500 ft contours to the southwest of the downdip extreme of the canyon suggest an associated incipient canyon (Fig. 8).

The Yoakum canyon shows features similar to modern delta-associated submarine canyons. Five extant, delta-associated, submarine canyons were examined and compared to the Yoakum canyon. These include the Swatch of No Ground (Ganges and Brahmaputra delta complex), the Swatch (Indus delta), the Mississippi canyon, the Niger delta canyons, and the Congo canyon. All these canyons are straight to slightly sinuous, have a scalloped wall morphology, and have overall gradients of 0.5° to 0.6°. In these respects, all are essentially identical to the Yoakum canyon (no gradient information or detailed morphology is available for the Niger canyons). Maximum depths for these canyons range from 2952 ft (900 m) for the Swatch to 4000 ft (1220 m) for the Mississippi canyon. Lengths of the canyons vary from as little as 12 mi (20 km) for the Niger Avon canyon to 70 mi (113 km) for the Swatch of No Ground. All the canyons trend parallel to the dip of the shelf except for the Swatch of No Ground, the position of which is controlled by bounding faults. The Swatch and the Mississippi canyon, like the Yoakum canyon, have localized reverse gradients. Like the Yoakum canyon, all are positioned off the front or to the side of a major delta, with the exception of the Congo canyon which indents inland forming an estuary at the mouth of the Congo river (Shepard and Dill, 1966, Burke, 1972, Coleman, et al., 1983).

Yoakum Canyon-fill Bedding Geometry

Internal bedding geometry of the Yoakum canyon, as determined from seismic profiles, shows evidence for aggradational filling including uplap against the walls of the canyon and onlap landward against the canyon floor (Fig. 11). Bedding within the canyon-fill is discontinuous near the basal unconformity but is less disrupted in the upper section. The Mississippi canyon has similar internal bedding characteristics (Coleman, et al. 1983).

STRATIGRAPHIC AND PALEOGEOGRAPHIC RELATIONSHIPS

Middle through Upper Wilcox Stratigraphy

The Wilcox Group can be divided into three major units, the "Lower Wilcox", the "Middle Wilcox", and the "Upper Wilcox" (Fig. 12). In this study the Yoakum shale, located between the "Middle Wilcox" and the "Upper Wilcox", is treated as a separate unit. The "Lower Wilcox" is a thick, sand-rich, progradational sequence which was deposited during the late Paleocene. The "Lower Wilcox" predates Yoakum canyon incision and is not included as a part of this study.

The "Middle Wilcox", which transitionally overlies the "Lower Wilcox" progradational sands, consists of a thick, dominantly aggradational shale sequence which is capped by a progradational sand sequence. For the purposes of this study the "Middle Wilcox" has been divided into two operational units, the lower Middle Wilcox and the upper Middle Wilcox. The upper Middle Wilcox unit lies directly below the Yoakum shale and, for mapping purposes, is arbitrarily defined as being everywhere 200 ft (61 m) thick. It is composed of the sand-rich, mixed progradational and aggradational section at the uppermost portion of the "Middle Wilcox". The lower Middle Wilcox operational unit is defined as that section between the "Lower Wilcox" and the upper Middle Wilcox unit.

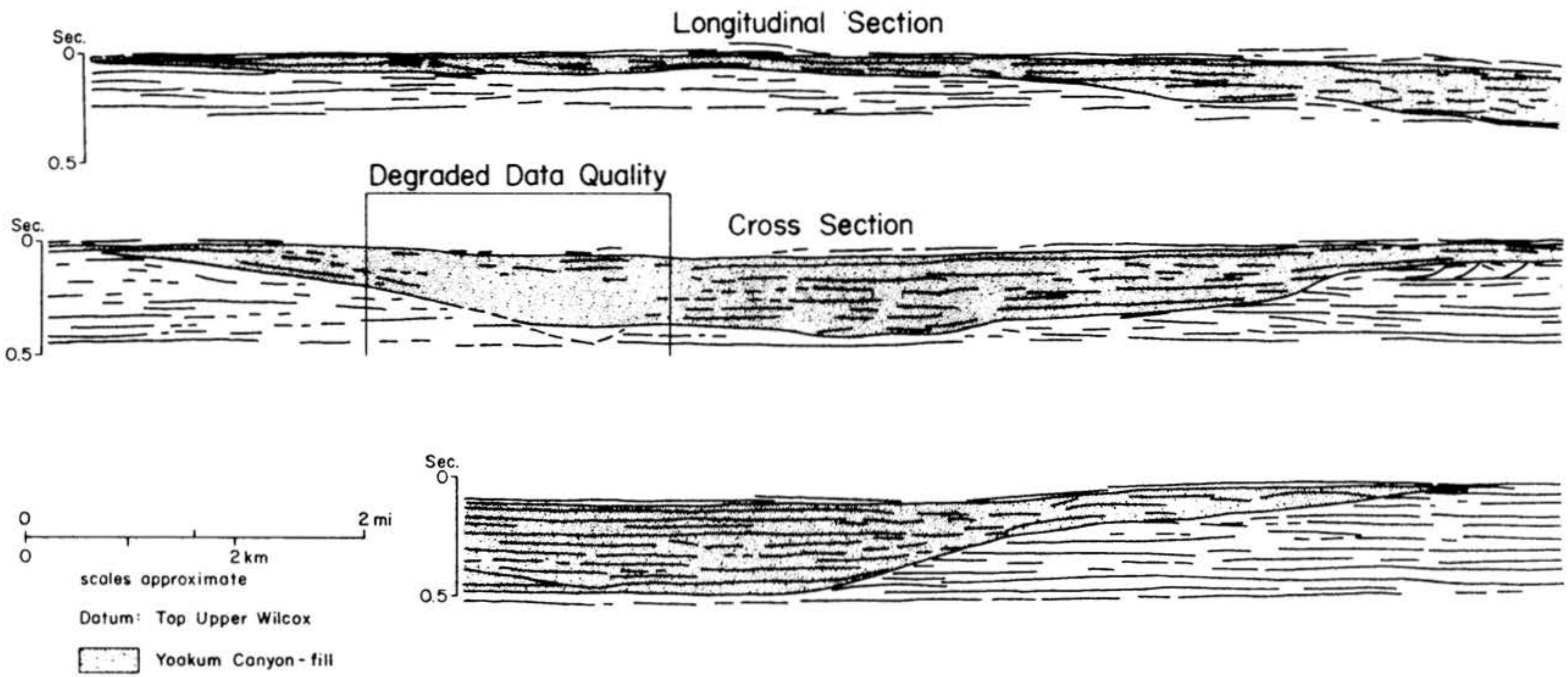


Figure 11: Seismic form lines of the bedding geometry of the Yoakum canyon-fill.

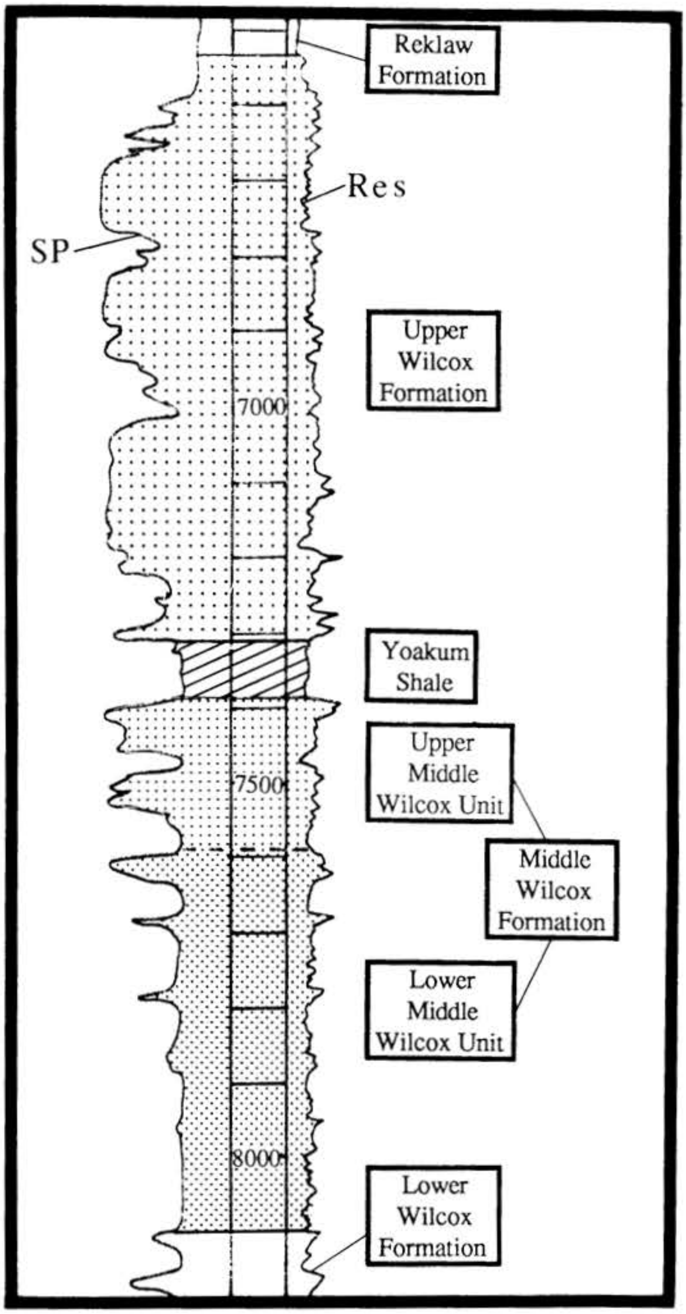


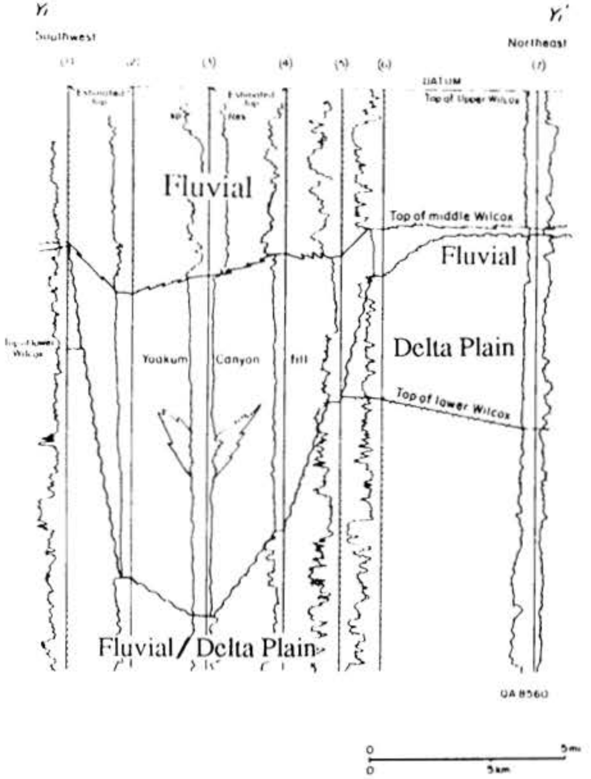
Figure 12: Type log (Texas Gas Exploration Co., A. Schumacher #1, Dewitt Co. (Fig. 7)) for the Middle and Upper Wilcox section showing the operational units (lower and upper Middle Wilcox, Yoakum shale, and Upper Wilcox) used in this study. Depths are in feet.

The "Upper Wilcox" is an extremely sand-rich, aggradational unit. Above its base, defined as the contact with the Yoakum shale, the Upper Wilcox section abruptly coarsens upward into a thick, aggradational section of sand with only minor strata of shale. The Wilcox Group is capped by the Reklaw Formation of the Clairborne Group, a marine shelf unit deposited following regional transgression of the Wilcox sequence.

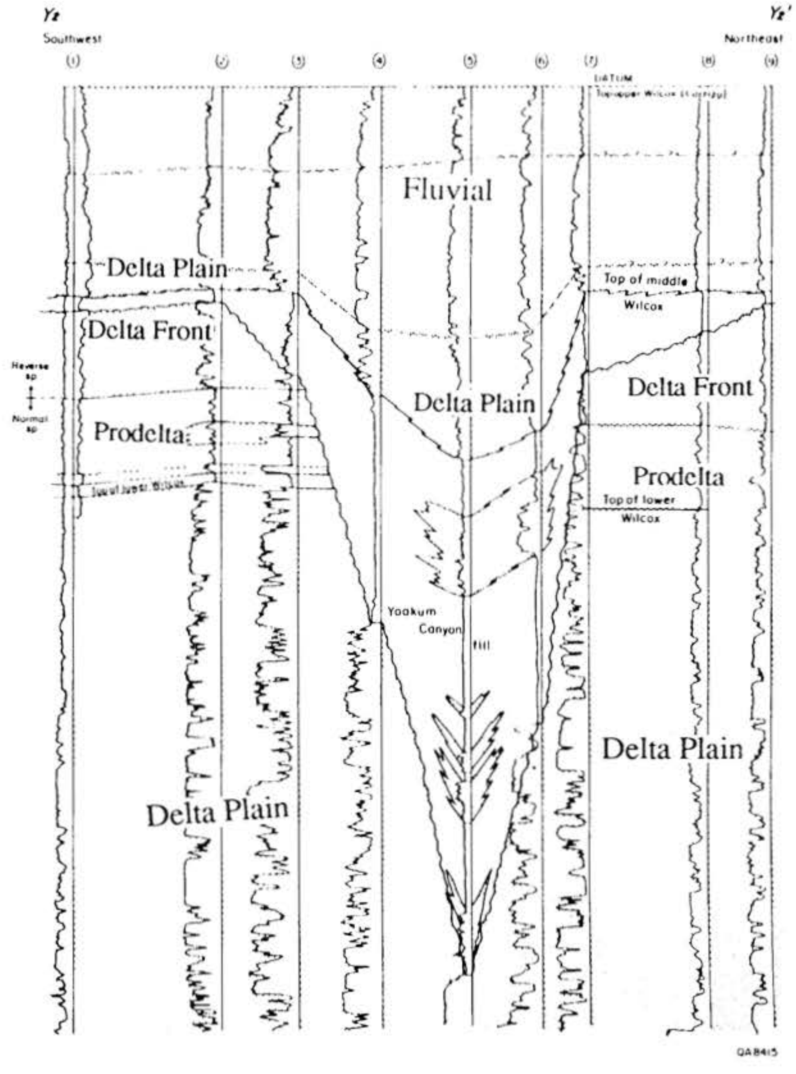
Contemporaneity of Yoakum Shale to Canyon-fill

The Yoakum shale was deposited at the same time as the upper part of the Yoakum canyon shale-fill during and/or immediately following the excavation of the Yoakum canyon. Besides the physical continuity between the upper part of the canyon-fill and the shelf shale and their lithologic similarity (Fig. 13), the best evidence for the age equivalence of these two intervals and for the near contemporaneity of canyon excavation and filling lies in the stratigraphy of a "chaotic zone" located adjacent to the canyon (Fig. 14).

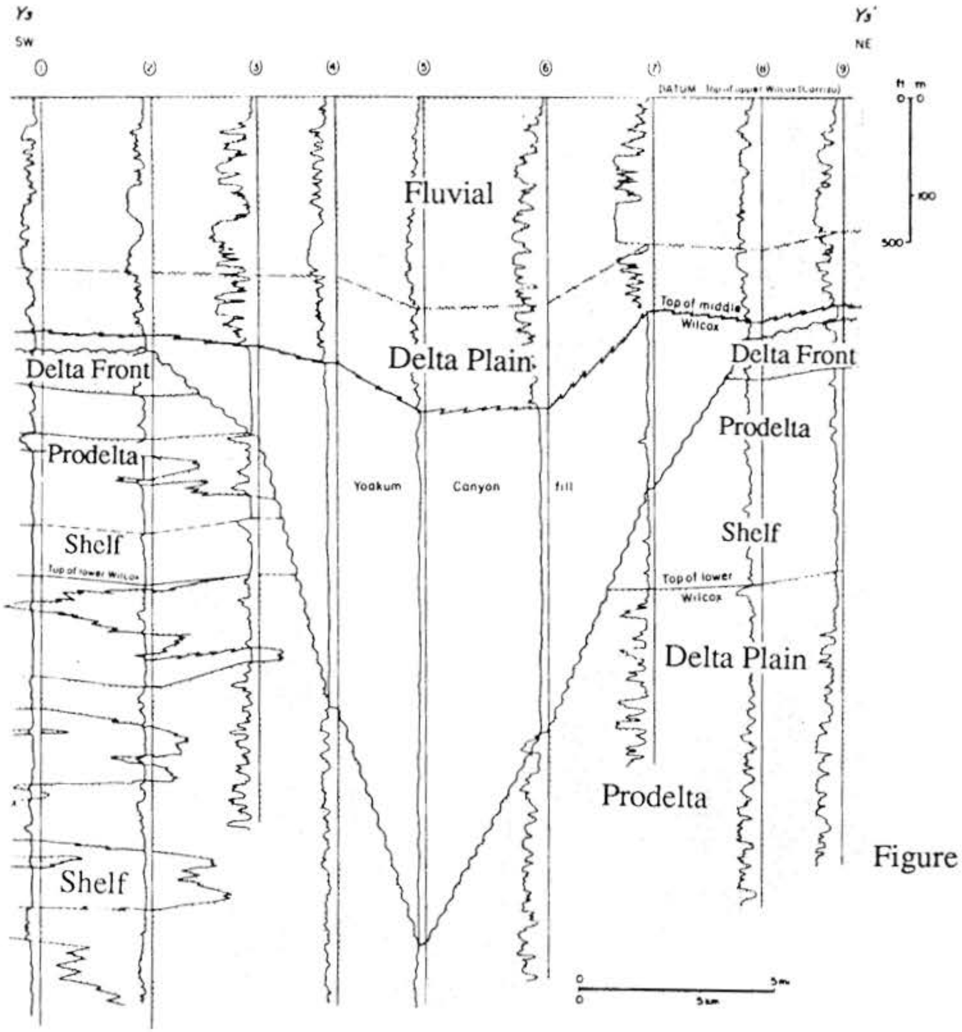
The "chaotic zone" has an arcuate morphology in plan view and is interpreted to consist of a "swarm" of incipient slumps. Identification and delineation of individual slump faults is impossible but their existence can be inferred in two ways. First, the thickness of the Yoakum shale is extremely variable within the "chaotic zone". Outside the confines of the canyon the Yoakum shale is of consistent thickness. Within the "chaotic zone", however, the Yoakum shale thickens above the presumed foot walls of the incipient slumps (Fig. 14). Rotation of slump blocks created excess depositional space above their foot walls. When the process of slumping within the "chaotic zone" was arrested this excess space was filled with the



Southwest
Northeast
DATUM
Top of Upper Wilcox
Fluvial
Top of middle Wilcox
Fluvial
Delta Plain
Yoakum
Canyon
fill
Top of lower Wilcox
Fluvial / Delta Plain
QA 8560



Southwest
Northeast
DATUM
Fluvial
Delta Plain
Top of middle
Wilcox
Delta Front
Delta Plain
Delta Front
Prodelta
Prodelta
Top of lower
Wilcox
Yoakum
Canyon
fill
Delta Plain
Delta Plain
QA 8415



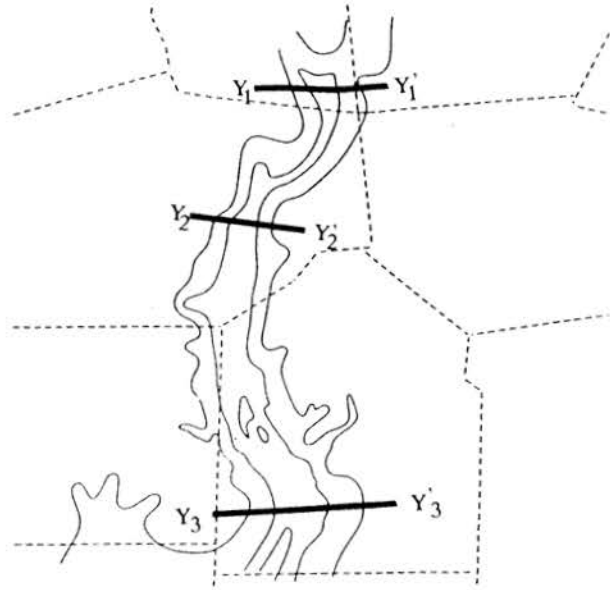


Figure 13: Stratigraphic cross-sections of the Yoakum canyon and surrounding Lower, Middle, Upper Wilcox sequences.

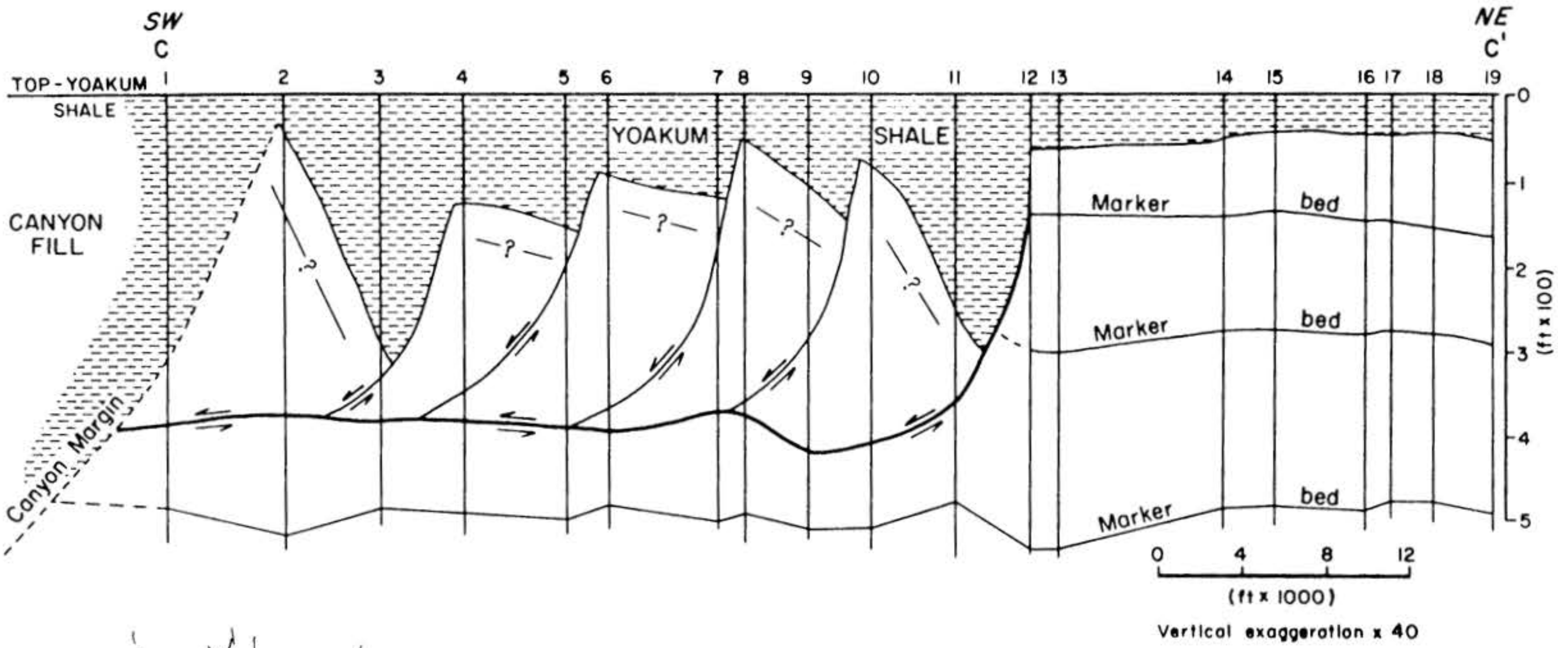


Figure 14: Cross-section and location map of the "chaotic zone" showing inferred incipient slump blocks as indicated by the variable thickness of the Yoakum shale and by the chaotic nature of Middle Wilcox marker beds. For well indentification see appendix II.

Yoakum shale and preserved.

The sands below the Yoakum shale within the "chaotic zone" provide a second indication of multiple slump faults. The upper Middle Wilcox sands can be correlated outside the borders of the "chaotic zone" by using electric log and seismic data. Within the "chaotic zone", however, correlation is confused due to faulting which not only moved hanging wall sands down relative to their stratigraphic, foot wall equivalents but tilted these sands out of the horizontal as well. Occasionally correlation of upper Middle Wilcox sands within the "chaotic zone" can be established between two wells but in each case the wells are a short distance from each other and the correlative "chaotic zone" section is less than the total thickness of the "chaotic zone". Such well pairs are considered to have part of their "chaotic zone" sections within the same fault block. The infrequency of such correlative pairs suggests the presence of many, separate slump blocks. The lower part of the Middle Wilcox section, approximately 400 ft (122 m) below the top of the Yoakum shale, can be correlated everywhere indicating the major slump plane became parallel to the bedding planes` at this depth.

The thalweg is assumed to have followed the deepest portion of the channel (Fig. 10). It bifurcated and flowed around a positive ridge adjacent to the "chaotic zone". Because seismic data indicate this mound is capped by the same unconformity as the rest of the canyon floor it is not considered to be a preserved slump deposit but, instead, is interpreted as a portion of the canyon floor temporarily shielded from current erosion by the presence of a slump deposit which was later removed. One of the deepest portions of the canyon (>3500 ft, 1067 m) lies directly upchannel of this positive feature. This "hole" was scoured by the erosive action of the back eddy created by the presence of the slump deposit and, after its removal by current action, this "hole" was preserved by the remnant canyon floor positive feature.

Preservation of the "chaotic zone" shows that the Yoakum canyon was formed in a marine environment and that deposition of the canyon-fill and Yoakum shale occurred immediately following the excavation of the canyon. Only in a marine environment, below wave base, could the "chaotic zone" slump topography have been preserved. Even marine reworking of these blocks of unconsolidated deltaic sediments at depth would have been sufficient to erase any record of their existence unless they had been immediately buried.

The increased thickness of the canyon-fill, as compared to the Yoakum shale outside the canyon, is the result of two processes. The most obvious is that much of the canyon-fill is composed of slump debris derived from the walls of the canyon. Such slump deposits contributed most, if not all, of the sand component of the canyon-fill. Slump deposits also contributed a large portion of the mud deposited within the canyon. Percent sand of the Middle Wilcox section decreases greatly below the top 200 ft (61 m) and, as the canyon is much deeper than this, a majority of slump debris was composed of silts and muds.

The depth of the canyon is the second factor contributing to the increased thickness of the canyon-fill. During trangression of the shelf water depths were much shallower outside the canyon. Consequently, muds were kept in suspension and not deposited except within the deeper, quiescent waters of the canyon. The hemipelagic portion of the deeper canyon-fill is therefore equivalent to a time of non-deposition on the shelf. With increased water depths and the renewed influx of the Upper Wilcox sediments the muds comprising the Yoakum shale were deposited. The topmost portion of the Yoakum canyon-fill is therefore both chronostratigraphically and lithostratigraphically equivalent to the Yoakum shale.

Regional Paleogeographic Setting

The Wilcox Group of sands and shales, together with the underlying shales (the Midway Group), represent the first thick, progradational wedge of clastic sediments to build out into the Gulf of Mexico along the Texas and Louisiana coasts (Bebout, et al., 1982; Fig. 2). The Lower Wilcox sediments prograded out over the shelf margin (established by the Lower Cretaceous Stuart City Formation) during early Tertiary time and extended the shelf-edge from 20 to 50 mi (32 to 80 km) basinward (Winker, 1982; Fig. 3). This outbuilding coincided with a major pulse of the Laramide orogeny (Winker, 1982, Ayers and Lewis, 1985). The great shedding of clastics from the Rocky Mountains provided an abundant sediment supply which formed massive delta complexes along the ancestral Texas coast. Later Miocene epeirogenic uplift of the western United States along with the simultaneously occurring orographic rainfall effect shifted the Gulf of Mexico depocenter to the Mississippi delta where it remains today (Ayers and Lewis, 1985, Winker, 1982).

The Rockdale delta system was the dominant depositional element of Lower Wilcox time (Fisher and McGowen, 1967). The Rockdale delta system was the ultimate site of deposition for the majority of Lower Wilcox sediments (60% areally and 80% volumetrically) (Figs. 15 and 16). Fisher and McGowen (1967) identified 16 individual delta lobes which make up the Rockdale delta system. These individual lobes were deposited during three phases of deltaic deposition in six separate delta complexes. The Rockdale delta was comparable to the modern Mississippi delta in size, facies distribution, and in the shapes, occurrence, and

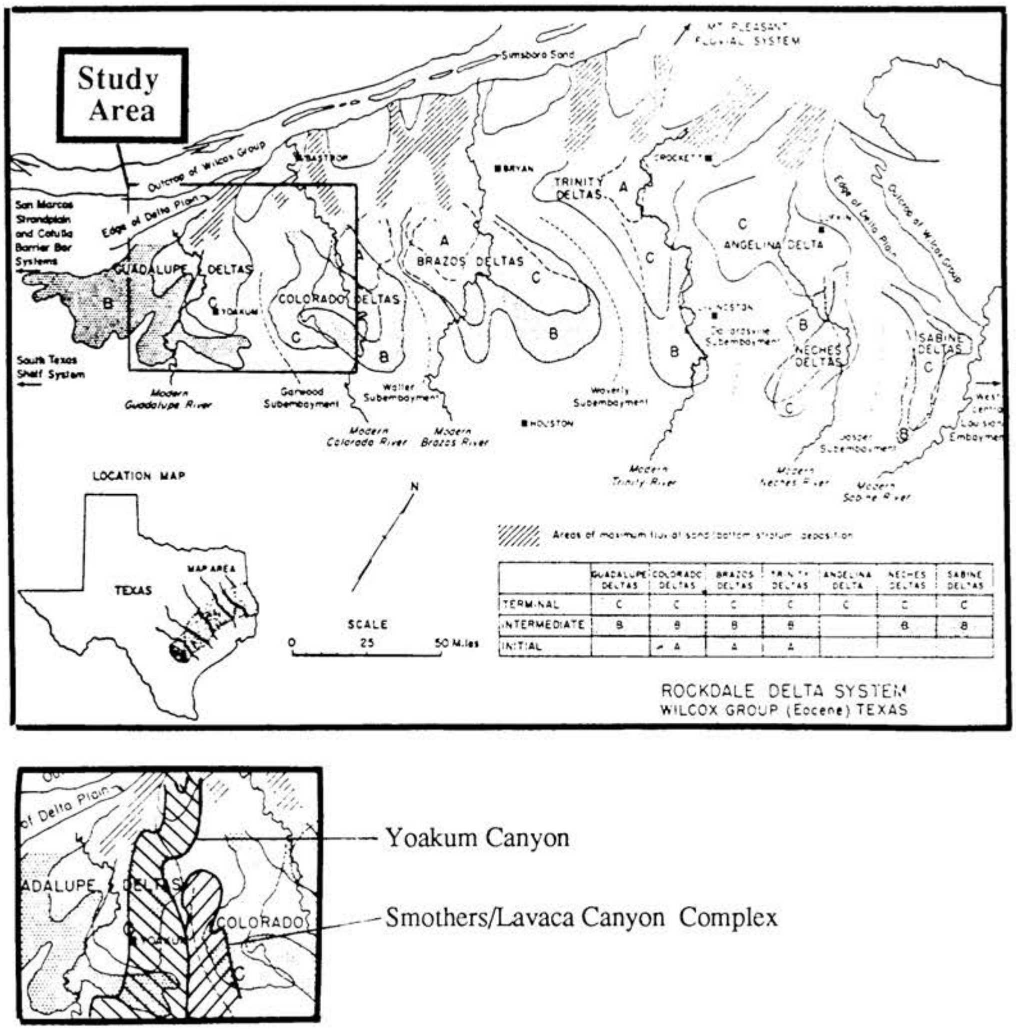


Figure 15: The Lower Wilcox Rockdale delta system (from Fisher and McGowen, 1967).

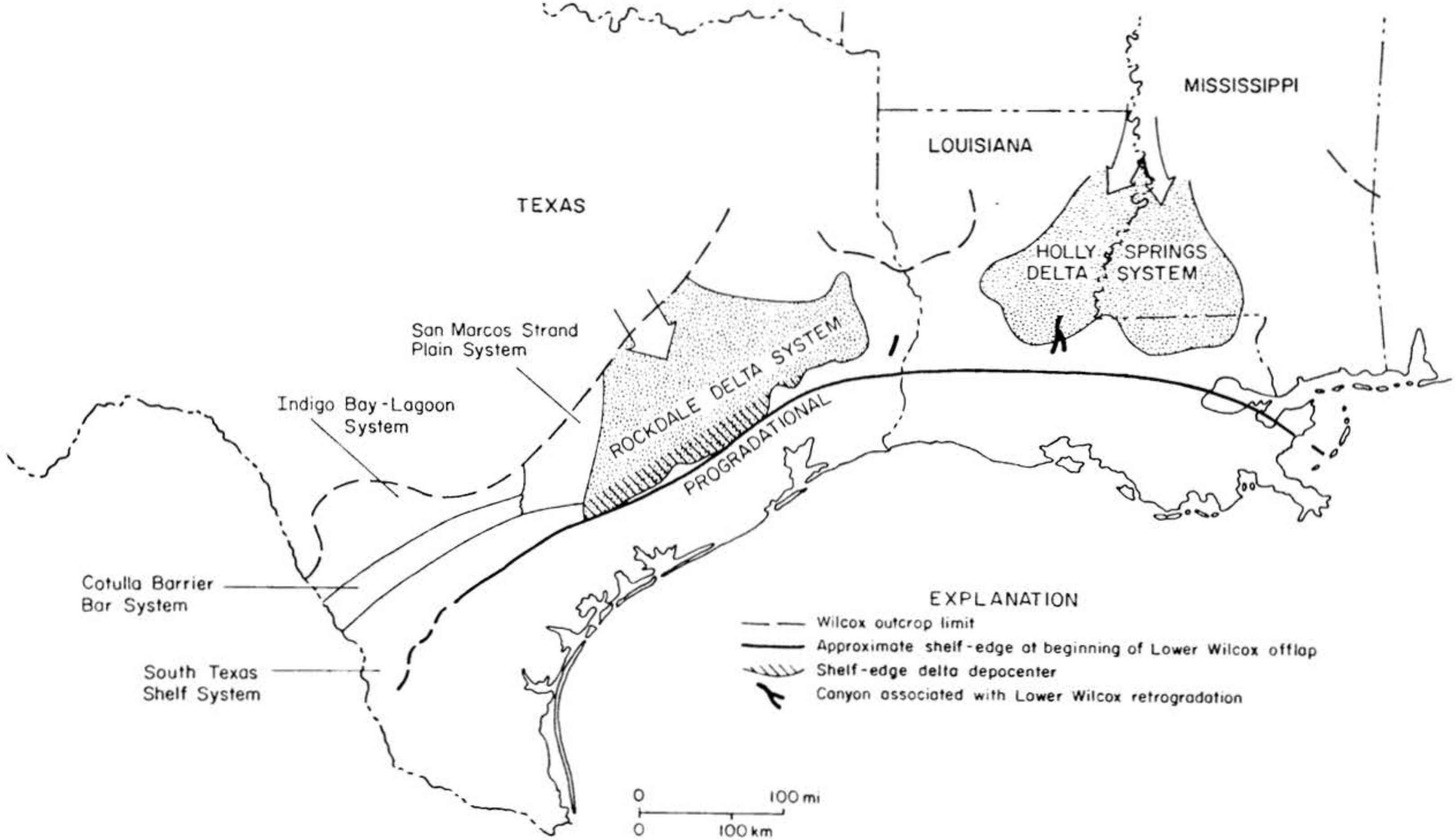


Figure 16: Lower Wilcox paleogeography (compiled from Ayers and Lewis (1985), Bebout, et al. (1982), Galloway (1968), and Fisher and McGowen (1967)).

position of the individual lobes (Fisher and McGowen, 1967).

During Middle Wilcox time the Rockdale delta remained active but sedimentation occurred at a greatly reduced rate (Ayers, 1985). Progradation ceased and the position of the shelf-edge remained stable until the renewed sediment influx of the Upper Wilcox (Winker, 1982) (Fig. 17).

Towards the end of Middle Wilcox time a resurgence of progradation occurred along with a shift in the site of the Texas Gulf Coast depocenter (Ayers and Lewis, 1985). The Rosita delta system, located within the Rio Grande embayment, became the sight of primary sediment deposition. First described by Edwards (1981) the Rosita delta system consisted of three major delta complexes. From oldest to youngest these include the Duval, the Zapata, and the Live Oak complexes and are named for the counties in which they were centered (Fig. 18).

Local Paleogeographic Setting

The paleoenvironment of the study area was determined through the interpretation of net sand maps, percent sand maps, and electrical log patterns in combination with review of the existing literature. Quantitative lithofacies mapping, in the form of net and percent sand maps, reveals the (1) positions of depocenters, (2) relative abundance of dip or strike-fed sand bodies, (3) areal and stratigraphic distributions of sand bodies, (4) positions of contemporaneous structures.

As an indicator of textural trends the electric log can be useful in the identification of paleoenvironment on two different scales. It can reveal small, individual features like paleochannels (a large deflection away from the base line in the SP and resistivity curves followed by a gradual decrease in amplitude may be

Figure 17: Middle Wilcox paleogeography (compiled from McCulloh and Eversull (1986), Ayers and Lewis (1985), Hamlin (1984), Galloway (1968)).

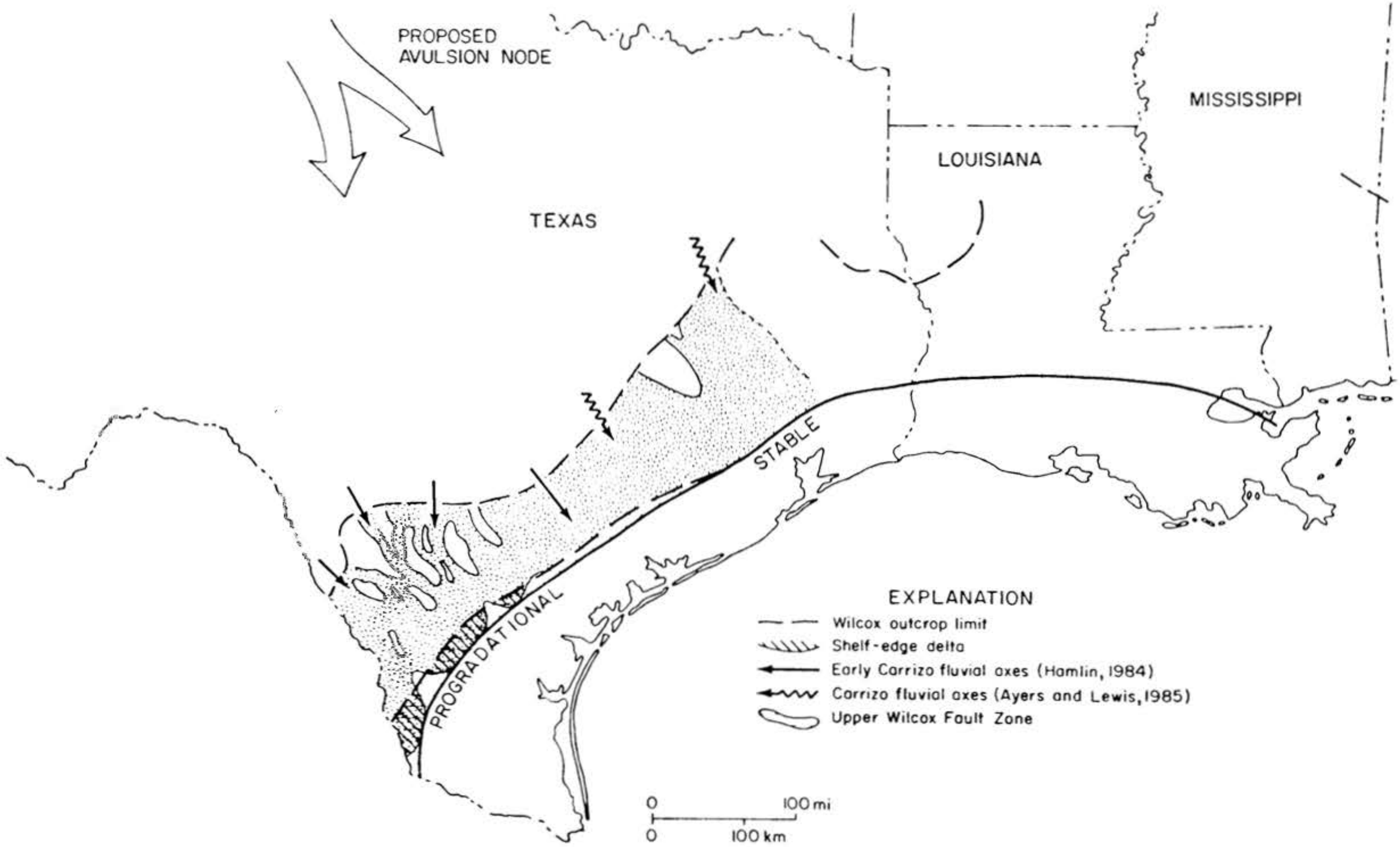


Figure 18: Upper Wilcox paleogeography (compiled from McCulloh and Eversull (1986), Ayers and Lewis (1985), Hamlin (1984), Edwards (1981)).

indicative of a scoured channel and fining-upward sequence) and, on a larger scale, the electric log can distinguish between overall progradational and aggradational trends over hundreds to thousands of feet of section.

The net and percent sand maps of lower Middle Wilcox operational unit have equivalent contour patterns (Figs. 19 and 20). Sand bodies are generally dip-oriented and trend north-south. Mud was the dominant sediment during lower Middle Wilcox time, especially in the downdip portion of the study area (where sand percent rarely exceeds 10%.) Electrical log patterns of wells which penetrated the lower Middle Wilcox section typically show a thick, homogenous shale which becomes coarser near its contact with the upper Middle Wilcox unit. Map contour patterns and electric log responses suggest the lower Middle Wilcox section within the study area represents the distal portion of a fluvially-dominated delta system.

The upper Middle Wilcox net sand map (Fig. 21) differs from the maps of the lower Middle Wilcox only in amount of sand. (Because the upper Middle Wilcox unit is defined as being everywhere 200 ft (61 m) thick the contour patterns for net and percent sand maps are identical). The size, distribution, and orientation of the sand bodies remained fairly constant throughout Middle Wilcox time and suggests that the upper Middle Wilcox section is simply the progradational delta front and delta plain continuation of the lower Middle Wilcox prodelta and shelf section.

The "Upper Wilcox" is very sand rich (Figs. 22 and 23). The sand bodies were still dip-oriented but the trend of these sand bodies, northwest-southeast, indicates a shift in the direction of primary sediment input occurred after the time of Middle Wilcox deposition. Electrical log responses reveal the stacking of multiple, blocky sand bodies indicating that aggradational, fluvial deposition dominated in the study area during Upper Wilcox time.

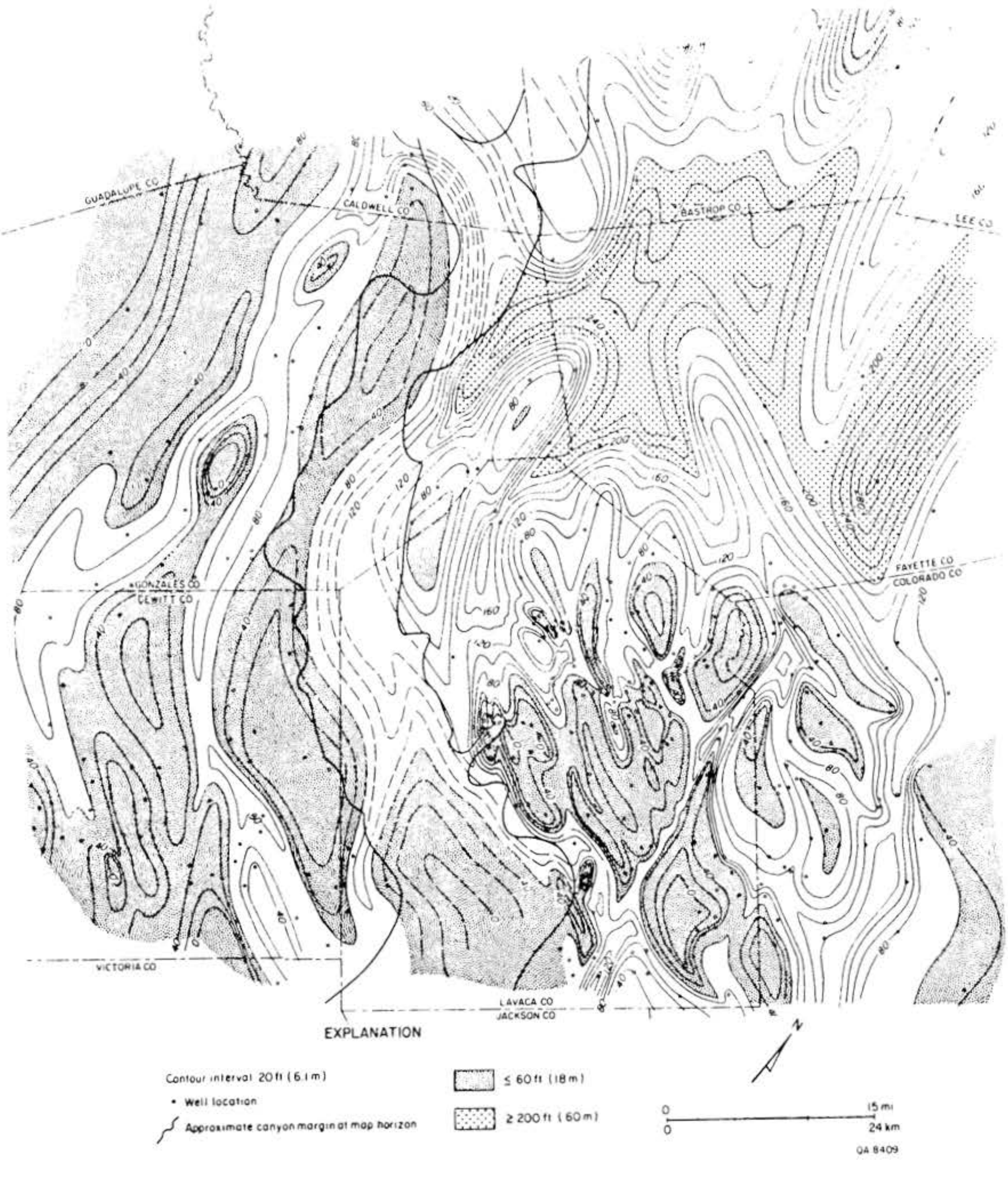


Figure 19: Net Sand isopachous map of the lower Middle Wilcox operational unit.

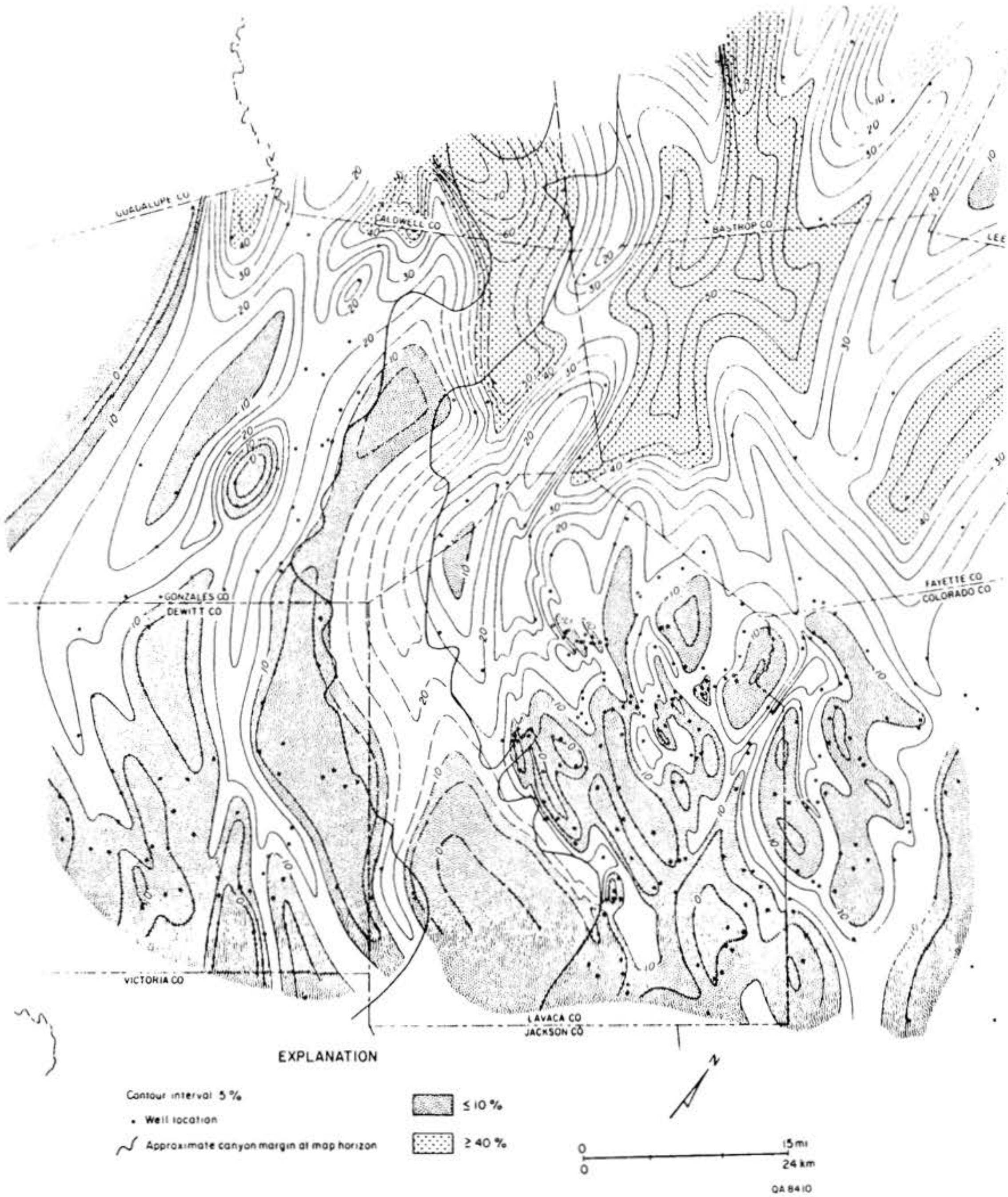


Figure 20: Percent sand map of the lower Middle Wilcox operational unit.

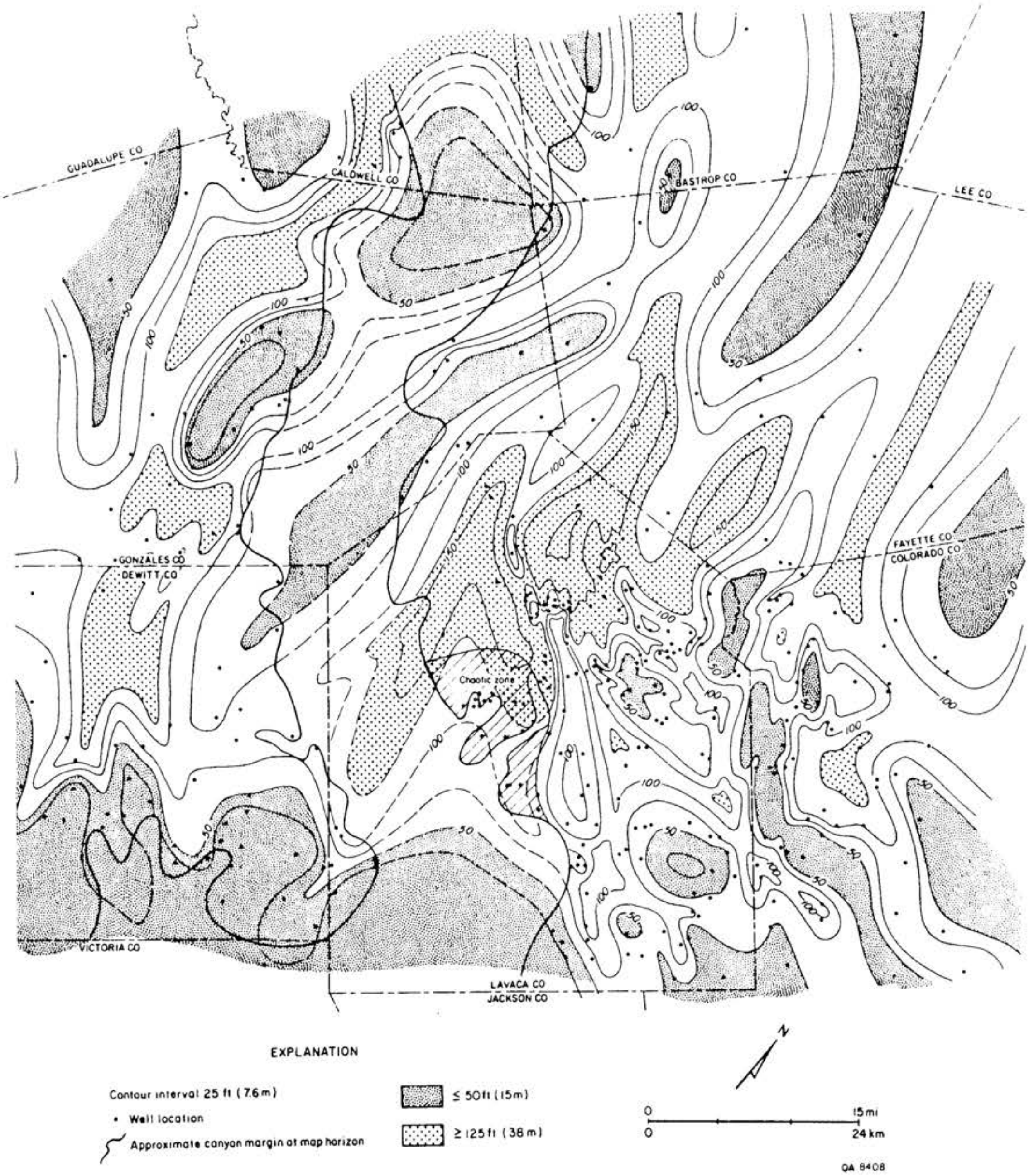


Figure 21: Net Sand isopachous map of the upper Middle Wilcox operational unit. (Since the upper Middle Wilcox is defined as being everywhere 200 ft (61 m) thick the net sand and percent sand contours are identical.)

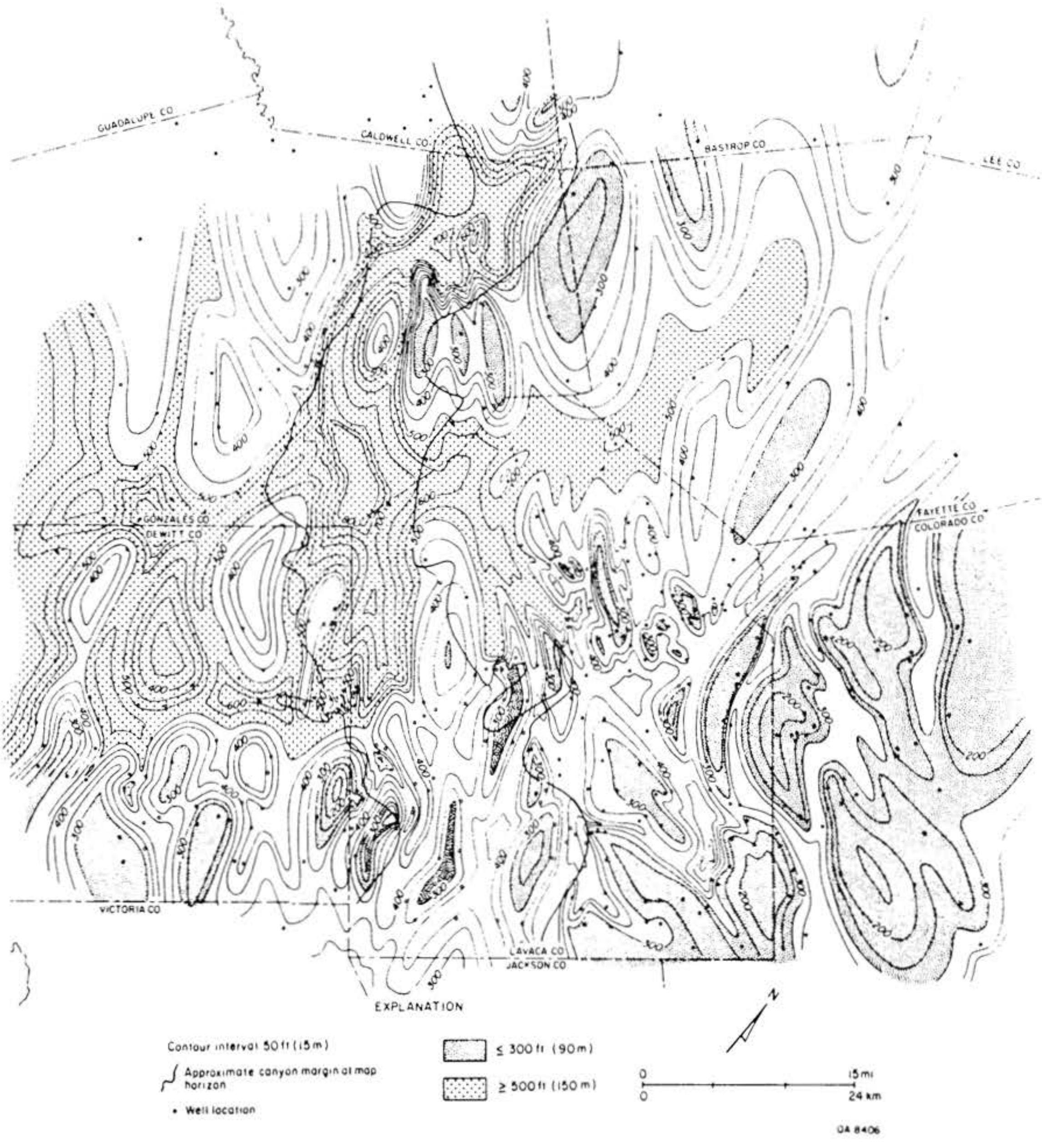


Figure 22: Net Sand isopachous map of the Upper Wilcox operational unit.

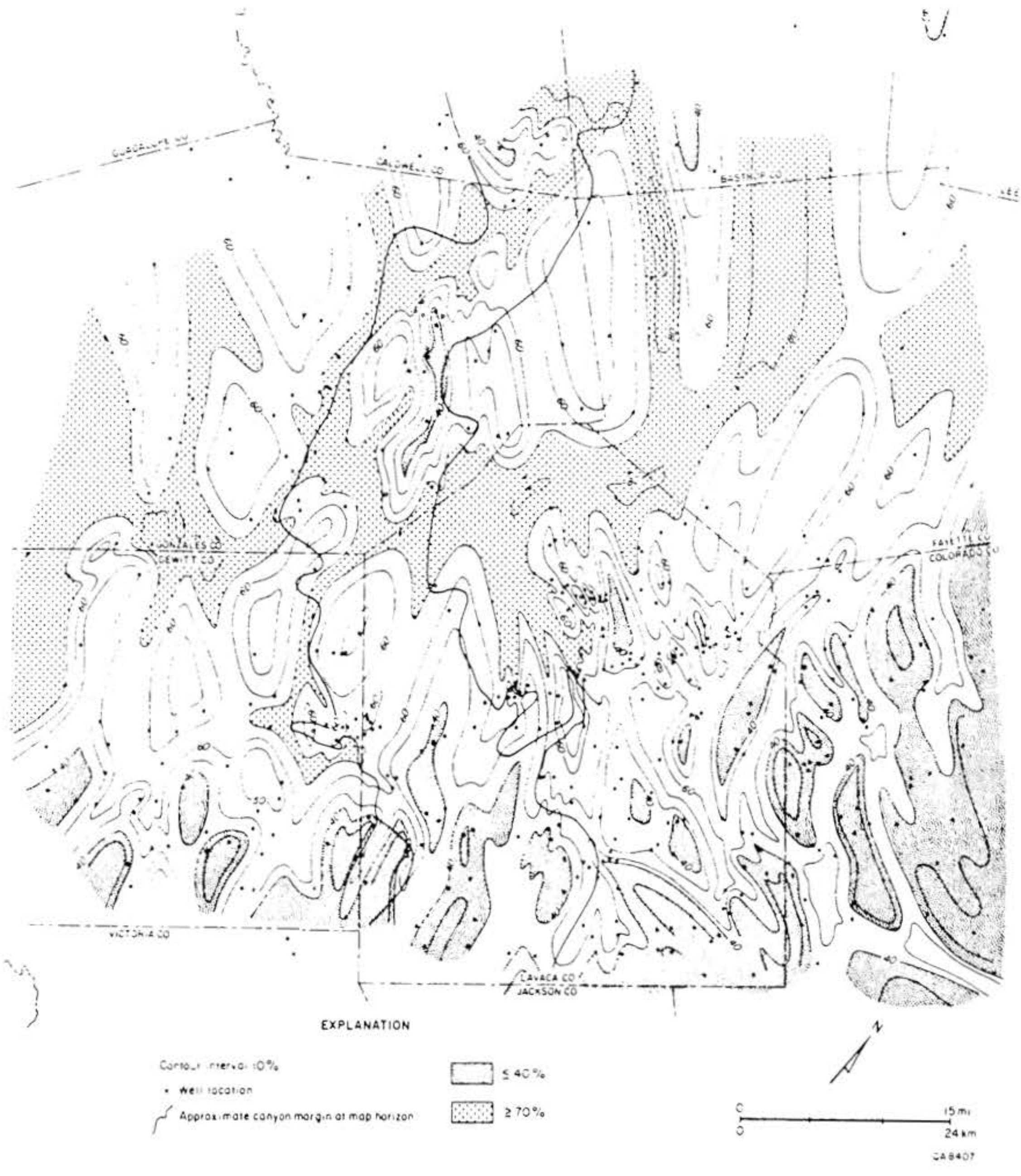


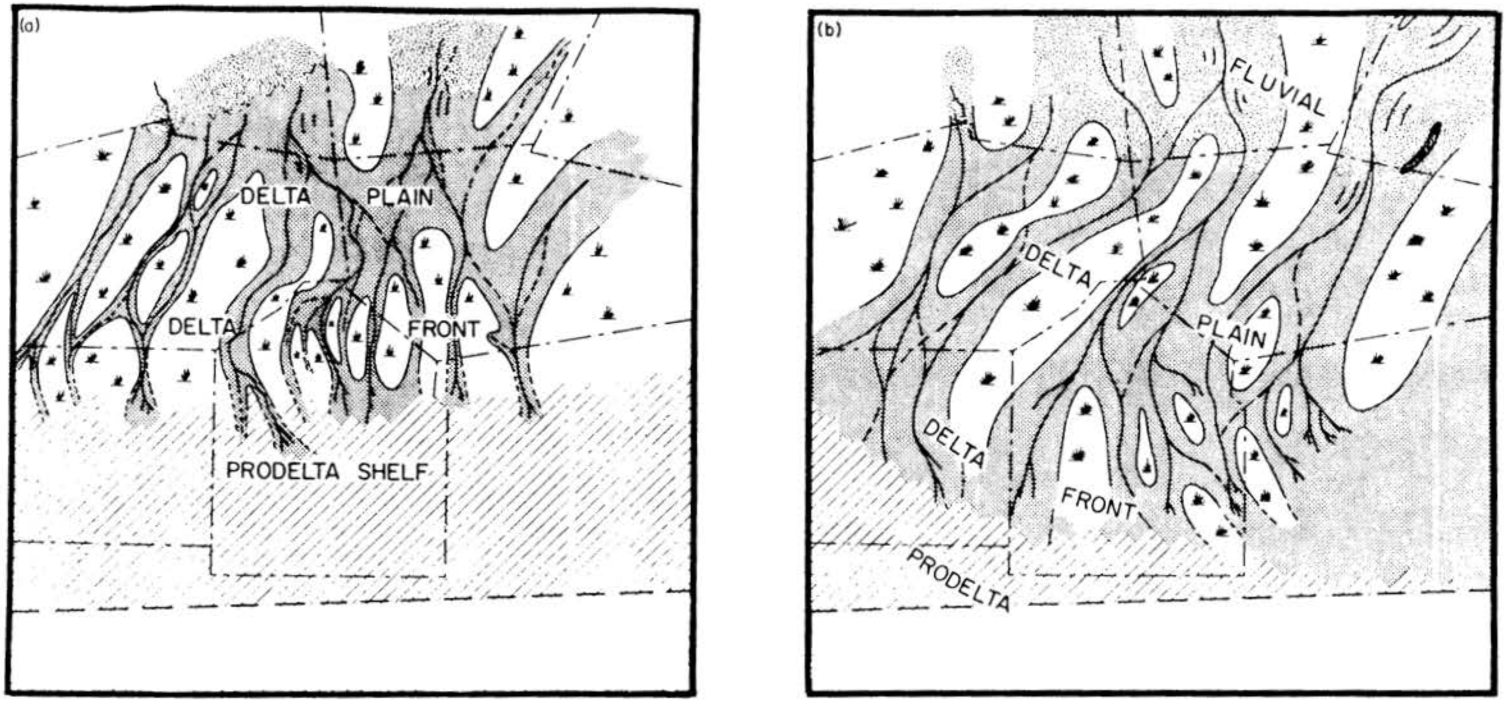
Figure 23: Percent sand map of the Upper Wilcox operational unit.

Quantitative lithofacies maps and electrical log responses were used to generate paleogeographic maps for lower Middle Wilcox through Upper Wilcox time (Fig 24, A-D). Figure 24a shows the lower Middle Wilcox as a time of deltaic deposition in the updip section of the study area. However, the absence of sand in the southeastern half suggests that only the deposition of distal prodelta muds was occurring in the downdip region during this time. During upper Middle Wilcox time (Fig. 24b) the delta had built out to the shelf edge in the southeast corner of the study area. Blocky SP and resistitivy log responses indicate fluvial depostion began to dominate in the extreme updip portion of the area. The primary sediment source was from the north, the direction of the rejuvenated Rockdale delta system (Ayers, et al., 1985).

Figure 24c shows the paleogeographic setting during Yoakum time. Inundation of the shelf resulted in the deposition of only hemipelagic and prodelta muds within the study area during this time (as well as gravity resedimentation within the canyon.)

Upper Wilcox fluvial/deltaic deposition rapidly extended across this shallow shelf and progradation again extended the shelf-edge basinward (Fig. 24d). Sudden shifts in electric log response indicate that Upper Wilcox deltaic progradation was extremely rapid and the majority of the section is made up of aggradational, fluvial deposits. Source direction for the Upper Wilcox sediments appears to be from the northwest, the direction of the Rosita Delta system, the presumed source for these sediments (Edwards, 1981, Ayers, et al., 1985).

Temporal Relationships



(a)
DELTA
PLAIN
DELTA
FRONT
PRODELTA SHELF
(b)
FLUVIAL
DELTA
PLAIN
DELTA
FRONT
PRODELTA

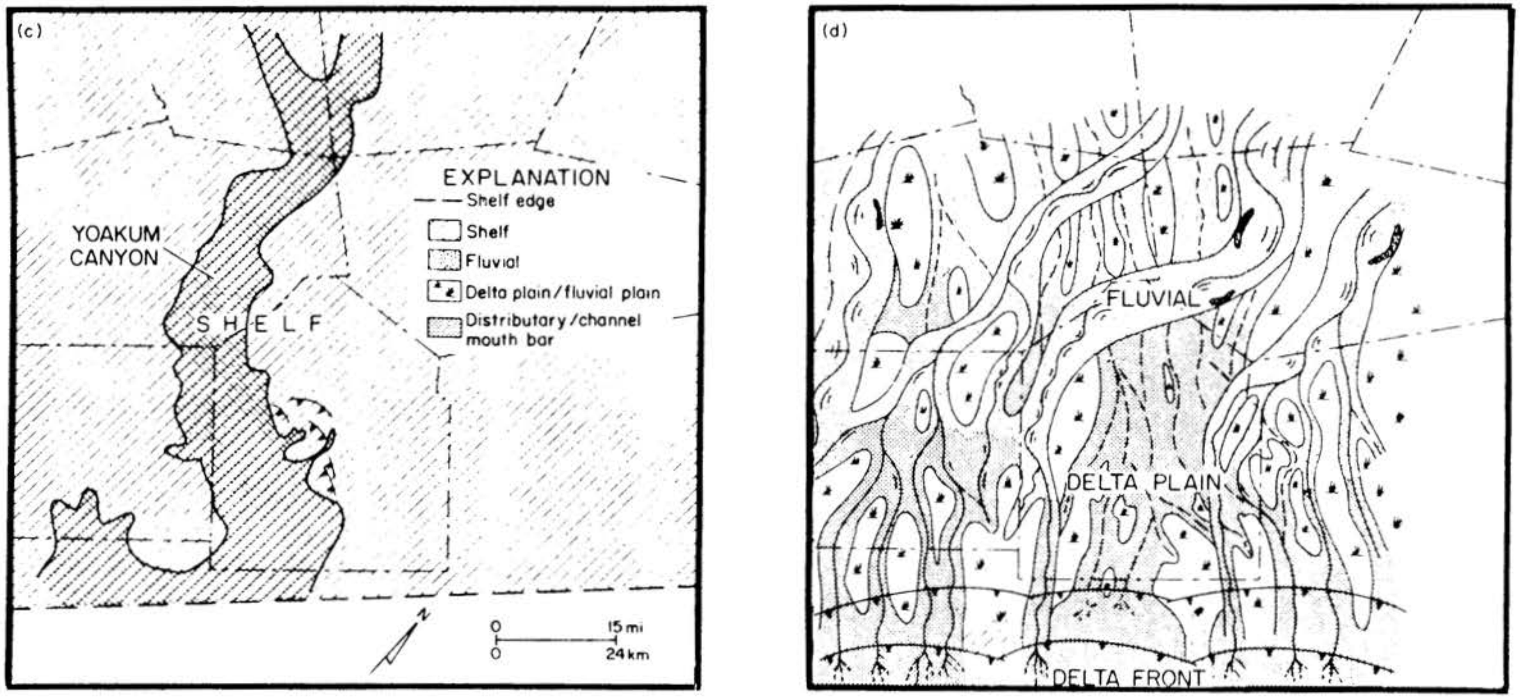


Figure 24: Paleogeographic maps of A) lower Middle Wilcox time, B) upper Middle Wilcox time, C) Yoakum time, and D) Upper Wilcox time. Note that Middle Wilcox delta prograded to, but did not extend, the shelf-edge.

Establishing the amount of time represented by the Yoakum shale and the time required to cut and/or fill the Yoakum canyon is difficult at best. Micropaleontological zonation of the Wilcox Group is poorly defined. Figure 25 shows that canyon cutting and filling occurred during the period of zone P6b, which had a duration of approximately 1.5 million years. However, the duration of zone P6b is a poor estimate because it also encompasses a large portion of both Middle and Upper Wilcox time.

The Yoakum shale outside the canyon comprises about 1% of the thickness of the entire Wilcox section. The duration of Wilcox deposition was approximately 10 million years (Fig. 25). If the rate of Wilcox deposition is assumed to have been constant, then the time required to deposit the Yoakum shale is 100,000 years. Since the Yoakum shale is probably underlain by a disconformity and since shelf muds are deposited at a slower rate than deltaic sediments this 100,000 year estimate can be considered an exteremly conservative minimum for the amount of time represented by the Yoakum shale section.

Another way to estimate the duration of cutting and filling of the Yoakum canyon is to compare it to a modern canyon. Coleman, et al. (1983) made a detailed study of the late Quaternary Mississippi submarine canyon and determined that it was excavated in approximately 7000 years and almost completely filled in the past 25,000 years (it is still filling today with pelagic sediments). These rates of canyon excavation and filling suggest that the formation of the Yoakum canyon, a feature approximately the same size as the Mississippi canyon, may have been geologically instantaneous.

The outcrop equivalent of the Yoakum shale is the Sabinetown Formation (Fisher and McGowen, 1967, Jones, preprint). The Sabinetown Formation is in the

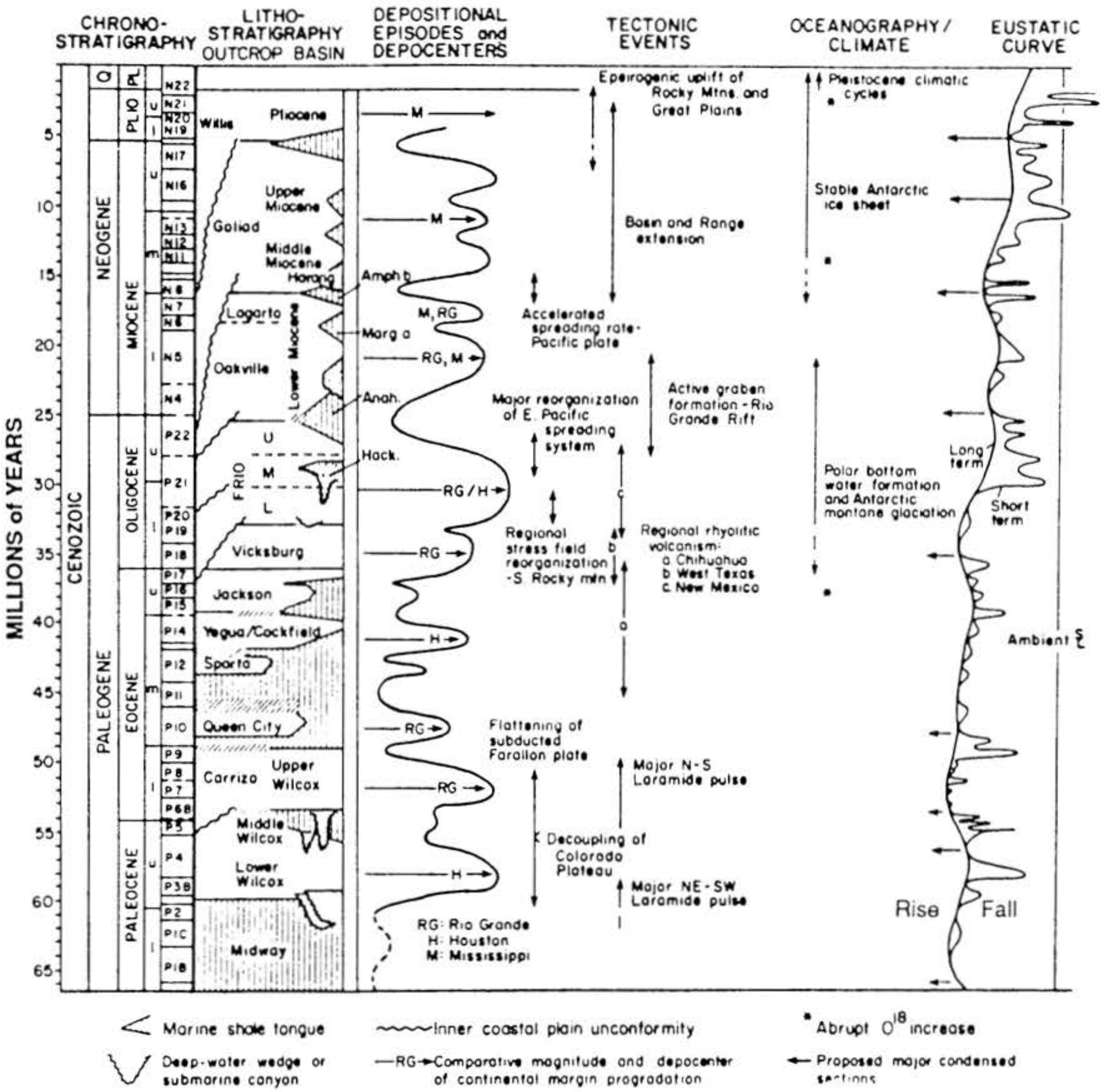


Figure 25: Comparative temporal history of Gulf Coast Cenozoic depositional episodes, proposed eustatic sea level changes, oceanographic evolution in response to Cenozoic climate cooling, and tectonic events of western North America. Major continental margin outbuilding and associated depocenters are shown by excursions on the episode curve (from Galloway, in press).

same stratigraphic position as the Yoakum shale, situated between the Rockdale Formation ("Middle Wilcox" outcrop equivalent) and the Carrizo Formation ("Upper Wilcox" equivalent) (Dodge and Posey, 1981). It is a thin, distinctive unit but poorly preserved with only local exposures. Sellards, et al. (1936) measured sections of the Sabinetown Formation during the late 1920's. They reported that "the Sabinetown beds were deposited in a transgressing sea that began with beach deposits and ended with deeper water deposition" (Sellards, et al., p. 604). Their interpretation was supported by descriptions of two measured sections which show the Sabinetown to be bounded by disconformities and composed of fine sands and shales. The presence of marine fossils, glauconitic sands, and a basal conglomerate provided support for their transgressive depositional model.

Outcrop work performed as a part of this study verified the general lithology of the Sabinetown Formation. Diagnostic exposures of the Sabinetown Formation were found along Sandy Creek on the Miller ranch (Fig. 26). Here the coarse, cliff-forming Carrizo sands contain large foresets and trough cross bedding. Near its lower contact the Carrizo Formation contains large mud clasts presumed to be rip up clasts derived from the Sabinetown section below. The contact itself is sometimes marked by an uneven surface with abrupt, erosional scours (<2 ft or 1 m deep) cut into the Sabinetown at irregular intervals. In other places, however, the contact is gradational. Similar Sabinetown lithology at other outcrop locations and both gradational and unconformable contacts have been reported by other authors (Murray and Thomas, 1945, Jones, preprint). The variable nature of the Sabinetown/Carrizo contact suggests that the contact was primarily conformable but that some of the Carrizo distributary channels initially cut down into the underlying Sabinetown section.

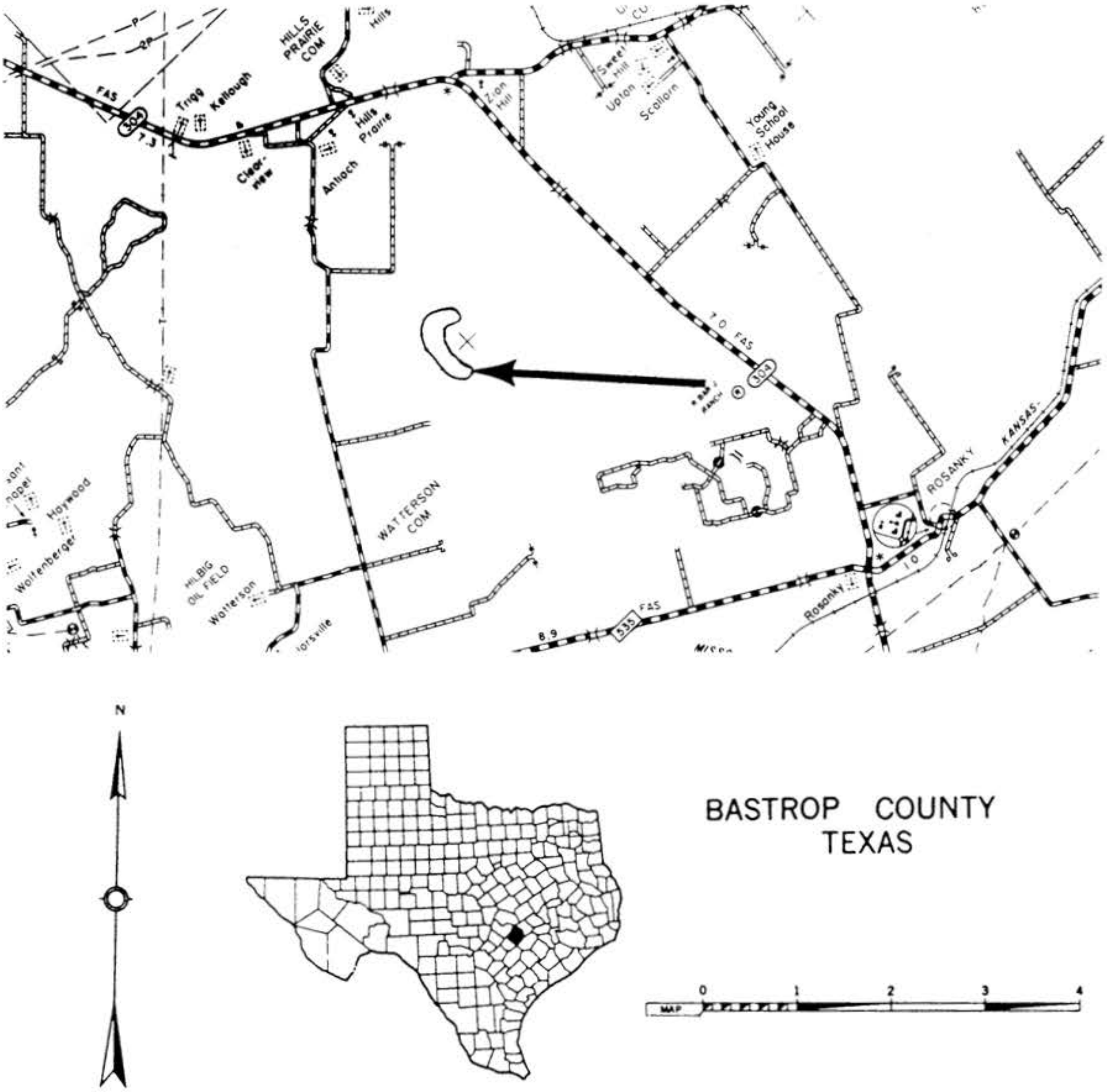


Figure 26: Location map for Miller Ranch outcrop located approximately six miles southeast of Bastrop.

The Sabinetown Formation varies from pure mudstone to muddy siltstone with a large percentage of carbonaceous material and some pyrite. It is green to orange in color with some layers of dark green, glauconitic sand. Bedding is locally angularly unconformable with the overlying Carrizo. However, the variability of both the angle and direction of dip of the bedding of the Sabinetown suggest that this angular unconformity is the result of syndepositional deformation caused by rapid loading.

The Losoya Creek outcrop, described by Sellards, et al. (1936), was located in an effort to verify their findings (Fig. 27). Degradation of the outcrop in the last sixty years, however, has obscured the lower contact and I was unable to verify the presence of marine fossils, pebble conglomerates and the existence of a lower unconformity.

The Sabinetown Formation and Yoakum shale represent a rapid marine transgression/regression with a total duration not greatly exceeding 100,000 years. Although it is possible to correlate the time of Yoakum canyon cutting and filling to a short term high stand on the eustatic sea level curve of Haq, et al. (1987), poor resolution makes it is equally possible to equate it to a relative low stand (Fig. 25). On the long term curve Yoakum time is located at the peak of a high stand, as is the majority of the Upper Wilcox deposition.

The Yoakum shale is a thin, widespread, marine deposit (Ayers and Lewis, 1985; Hoyt, 1959). The transgression which initiated its deposition must have been rapid with a duration on the order of 100,000 years. The only proposed mechanisms of eustatic sea level variation which could have induced such a rapid rise and fall of sea level are glacial eustasy and geoidal eustasy (Moerner, 1980). Eustatic sea level rise and fall, however, was not required for the deposition of the Yoakum

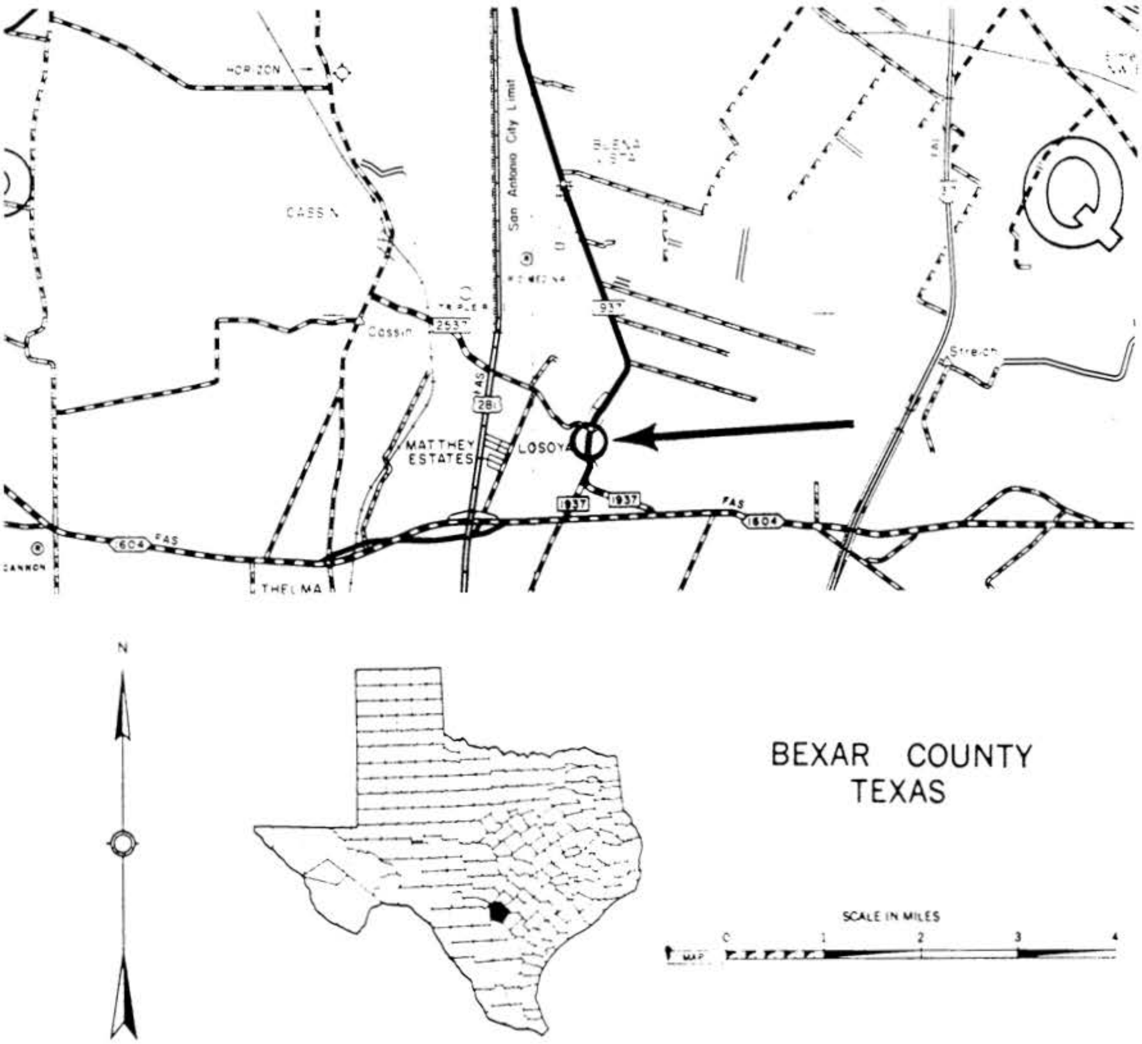


Figure 27: Location map for Losoya Creek outcrop located approximately five miles southeast of San Antonio.

shale. Subsidence of the basin margin, could have been sufficient to initiate such a transgression.

Winker (1979) stated that "isostatic adjustment to sedimentary loading takes place quickly, on approximately the same time scale as rapid Quaternary sea level changes." He made estimates of Quaternary subsidence rates for the Texas Gulf Coast by measuring the deformation of the Ingleside shoreline, a line of beach ridges deposited along the Texas and Mexico Gulf Coast approximately 100,000 years ago, and its stratigraphic equivalents. He estimated that subsidence rates have averaged 15 ft/1000 yrs (5 m/1000 yrs) at the shelf-edge decreasing to zero at the position of the hinge line, approximately 140 mi (225 km) inland. Assuming Yoakum deposition lasted 100,000 years this would translate into a relative sea level rise of 1500 ft at the shelf-edge with proportionately smaller values inland. Estimates of modern rates of tectonic subsidence for the present Louisiana Gulf coastline are on the order of 2 mm per year or approximately 60 ft (18 m) per 100,000 years (Jurkowski, et al., 1984). Subsidence rates at the shelf edge off the modern Louisiana Gulf Coast would be much greater. The presence of the canyon would have further enhanced the sediment starvation/subsidence process by funneling sediment to the basin floor which would have otherwise been deposited on the shelf (Ewing and Reed, 1984). Given the above data it seems unnecessary to call upon a eustatic sea level fluctuation to account for the Yoakum transgression. The required, rapid relative sea level changes are possible from subsidence alone provided sediment supply is greatly reduced. Winker (1982) and Ayers and Lewis (1985) suggested that the major river which fed the Rockdale delta complex underwent a regional avulsion at the end of Middle Wilcox time and began delivering sediment to the newly forming Rosita delta complex. Such an avulsion would have dramatically reduced the total volume of sediment entering the Rockdale delta system.

CANYON FORMATION

Processes

The morphology of the Yoakum canyon suggests that two processes, current scour and slumping, were primarily responsible for its excavation. The dip orientation of the canyon, its V-shaped cross section downdip, and the positioning of the apparent thalweg all suggest that erosion occurred at least in part by the down slope flow of an erosive current. Morphology suggests that the canyon bifurcated updip into smaller tributary canyons. This bifurcation was the result of the coalescing of individual density currents as they moved down slope.

Failure of the canyon walls in the form of slumping is the second major process responsible for canyon excavation. Multiple slump-scars create the scalloped morphology of the canyon walls (Fig. 9). Comparable slump morphology has been documented by Coleman, et al. (1983) in the late Quaternary Mississippi canyon (Fig. 28).

The Yoakum canyon is partially filled by slump debris. The areas of canyon-fill with the highest percent sand are often associated with the arcuate slump-scars of the canyon walls (Fig. 5). This is the result of the redeposition of canyon wall material, Middle Wilcox sands and shales, as slump debris within the canyon. Again, the Mississippi canyon serves as a recent analog. Coleman, et al. (1983) showed that the stratigraphically lowest levels of the Mississippi canyon-fill (comprising about one-third of the total canyon-fill) are thickest adjacent to major slump scars (Fig. 28a). They cite this as evidence that the stratigraphically lower

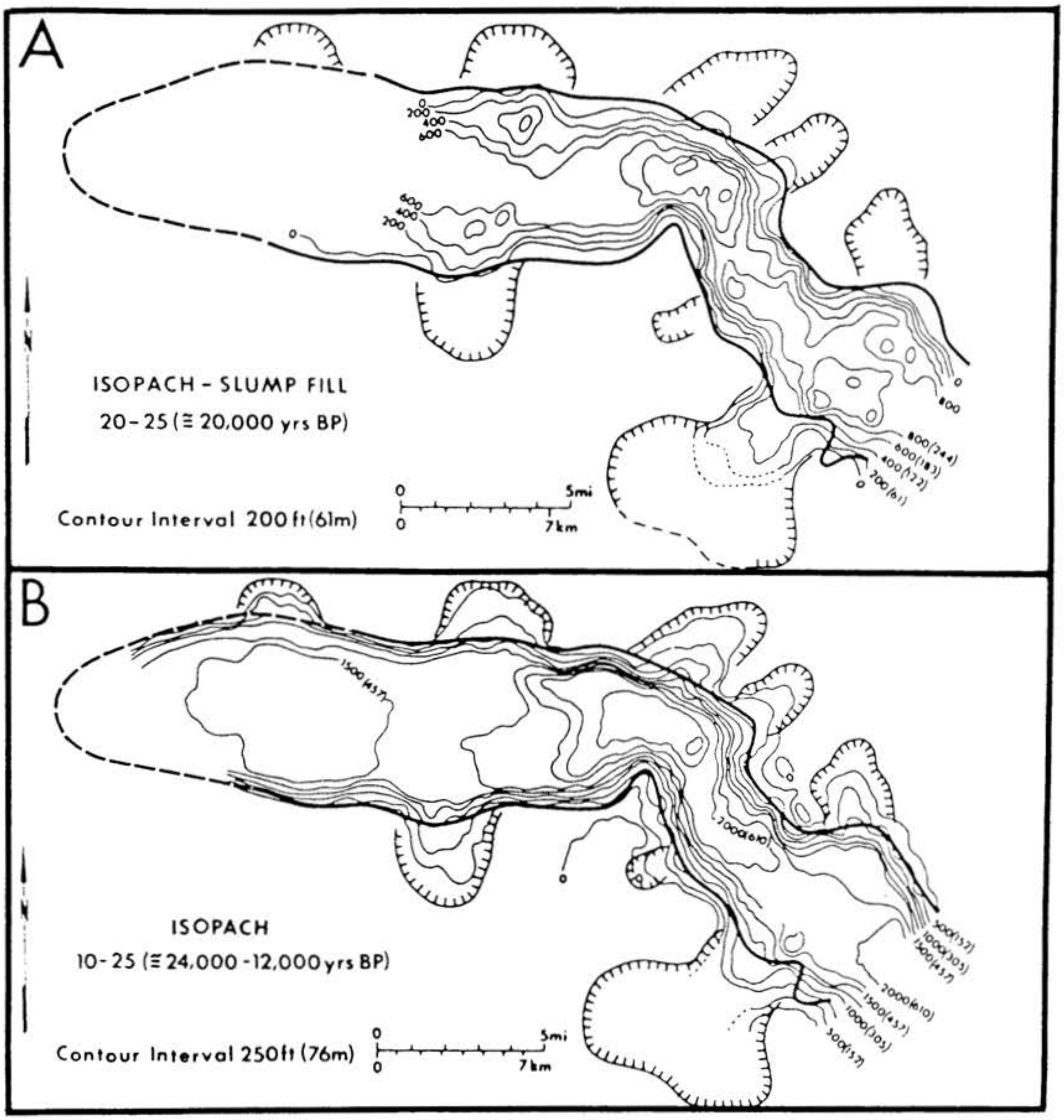


Figure 28: Isopachous maps of the late Quaternary Mississippi Canyon. A) Isopach of the slump-fill comprising the lower third of the canyon-fill unit. Note thickening adjacent to slump scars. B) Isopach of total canyon-fill (minus Holocene) (from Coleman, et al., 1983).

portion of the canyon filled, in part, with slump debris. The downdip portion of the Yoakum canyon-fill has little or no sand (Fig. 5). This lack of coarse fraction is interpreted to be the result of flushing of the original, downdip slumps by bottom-flowing currents. Subsequent, updip slumps were more likely to be preserved and, hence, the sand content of the canyon-fill is higher in the updip region.

The presence of the "chaotic zone", with its incipient slumps (already described), is further evidence not only that slumping was an active process but that slumping and filling were occurring simultaneously (Fig. 14).

Models of Canyon Formation

Three theories attempt to explain the presence of a canyon, an erosional feature, within an otherwise progradational continental margin setting. Vail, et al. (1977) updated the long-held theory that canyon formation occurs during periods of relative low-stand when sea level is below shelf-edge (Fig 29a). Many authors have related the Yoakum to such a fall (Ayers and Lewis, 1985, Hoyt, 1959, Chuber and Begeman, 1982). Under such conditions a river will incise a subaerial valley to the shelf-edge. Sediments delivered through this valley cause loading of the shelf-edge which in turn initiates slumping at the shelf-edge. Headward erosion by means of slumping plus current scour in the form of density underflows generated by river currents and turbidity currents enlarge the feature to canyon dimensions. During transgression canyon excavation via current scour and slumping continues until equilibrium is obtained. With rise in sea level and drowning of the shelf margin the canyon begins to fill with slump debris, hemipelagic and prodelta muds.

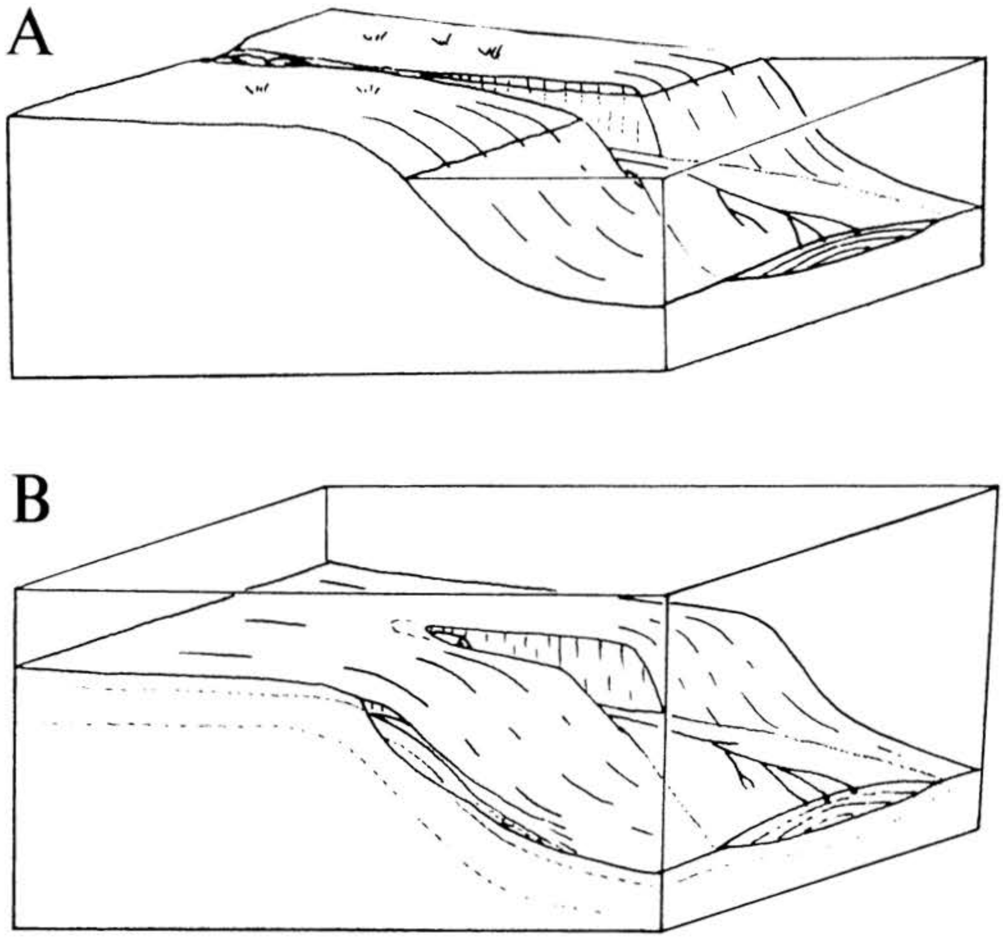


Figure 29: Schematic representations of canyon formation models.

A) sea level lowering below shelf-edge initiates canyon formation at the mouth of a pre-existing river (modified from Vail, et al., 1977). B) sea level rise and resultant sediment starvation initiates canyons in the form of headwardly retreating slump scarps (modified from Brown and Fisher, 1984.)

Other authors maintain submarine canyon formation does not require a sea level drop (Daly, 1936, Brown and Fisher, 1980, Farre, et al., 1983). Brown and Fisher's (1980) model requires a relative sea level rise in order for canyon formation via headward slumping across the shelf to occur (Fig. 29b). Sea level rise reduces the sediment supply to the shelf-edge. Retrogradation of the slope then occurs in the form of slumping at the shelf-break. A submarine canyon is formed when multiple slumps erode headward into the shelf sediments. When excavation ceases the canyon will fill with slump debris and hemipelagic mud.

Although Burke (1972), like Vail and others, calls for a drop in sea level to initiate canyon formation, he describes another factor which contributes to the formation and maintenance of submarine canyons. He documents that the submarine canyons which flank the Niger delta are kept open by the convergence of longshore currents within the bights on each side of the Niger delta headland (Fig. 30 and 31). These converging, longshore currents move offshore downslope as density underflows scouring the length of the canyon until they encounter the lower gradient of the basin floor and deposit entrained sediments as a submarine fan. Submarine canyons associated with the Niger Delta which were not positioned at the convergence of longshore currents became inactive.

The present study of the Yoakum canyon favors an interpretation of its formation based on a combination of the Brown and Fisher model and the Burke model. There is no need to call upon a drop in absolute sea level in order to explain the genesis of the Yoakum canyon. Subsidence, when accompanied by a sudden decrease in sediment supply, can result in water depths sufficiently deep for canyon formation. However, the Brown and Fisher model lacks a focal mechanism for erosion, an important element present in the Vail, et al. (1977) model. In the Vail, et

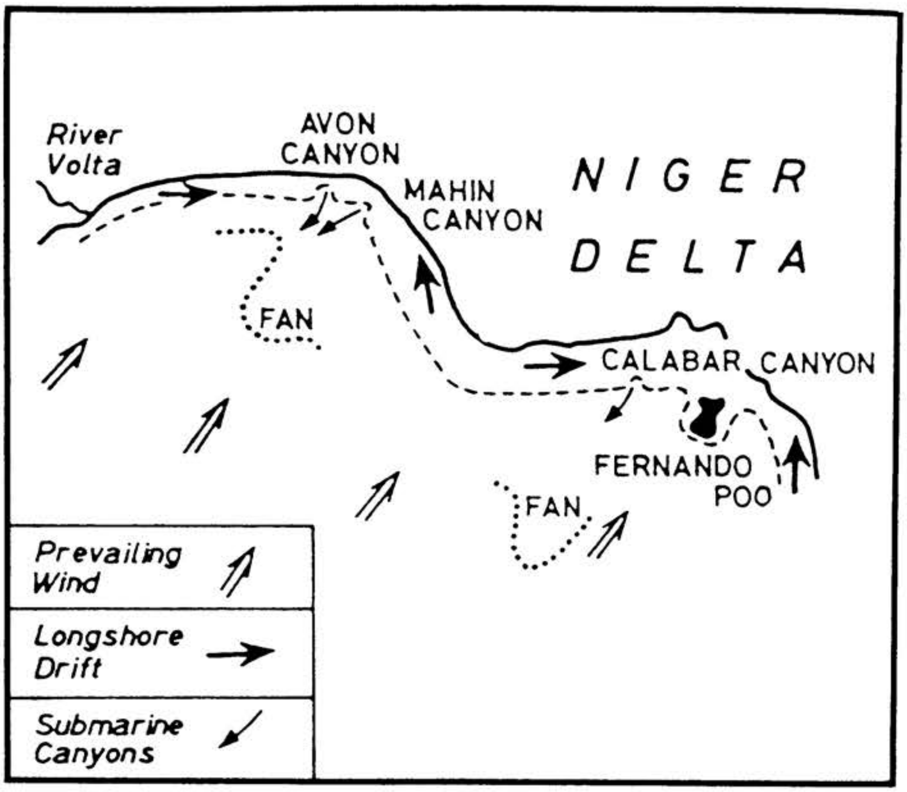


Figure 30: Convergent longshore currents move offshore as density underflows and maintain the canyons adjacent to the Niger delta (from Burke, 1972).

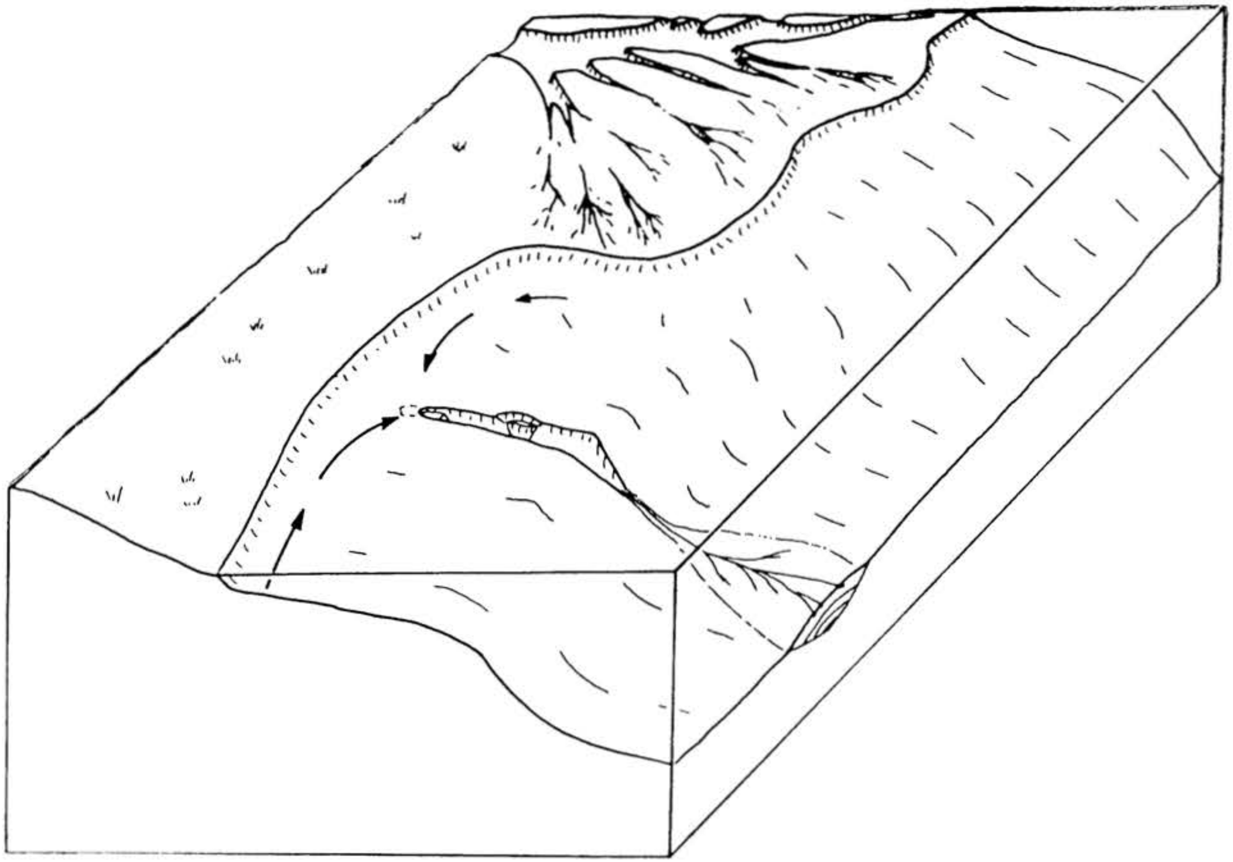


Figure 31: Schematic of how longshore current convergence may provide a focal mechanism for canyon erosion following canyon initiation via slumping at the shelf-break during transgression and high-stand submarine canyon formation (after Burke, 1972).

al. (1977) model the river acts as a focus for slumping and current scour. Farre, et al. (1983), in their model of canyon formation, maintain that the canyon itself, once it breaches the shelf break, acts as its own focal mechanism by capturing existing shelf currents. Such a capture of convergent longshore currents off the headland of the Middle Wilcox Rockdale delta is considered to have provided the point source necessary for the formation of the Yoakum canyon following a regional transgression (Fig. 31).

Yoakum canyon formation, then, began in response to a sudden shunting of the sediment supply followed by a subsidence-induced transgression. Canyon formation was initiated by slumping at the shelf break and was enhanced by a consistently oriented offshore current. Canyon formation was arrested when rate of sedimentation increased sufficiently for progradation to resume.

CONCLUSIONS

History of the Yoakum Canyon

The following is a detailed chronology of the events which led to the excavation and filling of the Yoakum canyon:

During late Paleocene time the Lower Wilcox sequence prograded over the preexisting shelf margin and advanced the shelf-edge basinward (Fig. 2). The Rockdale delta system was the center of deposition during Lower Wilcox time (Fisher and McGowen, 1967; Figs. 15, 16).

Middle Wilcox units were deposited during the retrogradation which followed Lower Wilcox deltaic deposition. The position of the shelf-edge remained unchanged until after Yoakum shale time (Winker, 1982). After a long period of deposition of prodelta muds and silts an increase in sediment supply rejuvenated the Rockdale delta system and upper Middle Wilcox deltas again prograded basinward (Ayers and Lewis, 1985). The Middle Wilcox deltas locally prograded out to, but did not significantly extend, the existing shelf-edge. Deposition of sand atop undercompacted muds created a density inversion and initiated large-scale slumping at the shelf-break.

At this time, the end of Middle Wilcox deposition, the volume of sediment entering the rejuvenated Rockdale delta system abruptly decreased due to a major avulsion of the primary river (Ayers and Lewis, 1985; Fig. 18). Flow was redirected toward the Rio Grande embayment to the southwest. Ayers and Lewis (1985) proposed that this avulsion lead to an immediate switching of depocenters and that deposition of Rosita delta sands occurred simultaneously with deposition of the Yoakum shale. However, the Yoakum shale can be traced far to the southwest, at least partially into the area of the Rosita delta system (W. E. Galloway, personal comm.) and it seems more likely that a lag time existed during which neither delta system was dynamic.

With the diversion of the principal fluvial system, subsidence of the Rockdale delta system began to outstrip deposition and transgression ensued. Excavation of the canyon began soon after the onset of subsidence. The density inversion created by the Middle Wilcox progradation, sands atop unconsolidated slope muds, initiated slumping along the margin of the Middle Wilcox deltas. At the position of the Yoakum canyon, on the flank of the Middle Wilcox delta system, recurrent slumping was enhanced causing headward erosion into the shelf. The recurrent focus for slumping at the position of the Yoakum canyon was caused by a basinward directed density underflow. This bottom current aided in excavation directly by scouring the floor of the canyon, and indirectly by undercutting the walls of the canyon and accelerating the process of slumping.

Converging longshore currents, like those active adjacent to the modern Niger delta (Burke, 1972), were responsible for the positioning of a major canyon on the southwest flank of the Rockdale delta system. Longshore currents moving north toward the delta complex converged with similar currents moving to the south off the delta headland. If the rejuvenated Middle Wilcox Rockdale delta system conformed to the same pattern of delta distribution observed during Lower Wilcox time then there may have existed a second order of focussing to any converging currents because the Yoakum canyon was located in the bight between the Guadalupe and Colorado delta complexes.

Excavation of the canyon ceased when subsidence rates decreased (or sedimentation rates increased) sufficiently for progradation to resume. With increased sediment load the ability of the density underflow to entrain additional sediment decreased and deposition began. Slump debris and hemipelagic mud began to fill the canyon. As sedimentation rate increased suspension deposition constituted a growing percentage of canyon-fill and slumping declined. The remaining canyon-fill was made up of the prodelta muds of the advancing Upper Wilcox deltas. The Yoakum canyon was completely filled by the time Upper Wilcox sands prograded over the area. Compaction of the canyon muds resulted in a thicker Upper Wilcox section above the canyon, particularly in the basal, progradational sequence.

Pertinence to the General Problem of Canyon Formation

Like most geomorphological features, submarine canyons form under a variety of conditions. The only three requirements shared by all submarine canyons are 1) submergence 2) the existence of an erosional environment and 3) preferential erosion creating an elongate feature.

Erosion does not require subaerial exposure. Although a low stand of sea level would certainly initiate the formation of submarine canyons, many, like the late Quaternary Mississippi canyon, must have been generated during intermediate to high stands of sea level. Erosion of the Yoakum canyon, like the Mississippi canyon, was initiated by a process of gravity redistribution of shelf sediments.

There are several causes for the linear erosion of submarine canyons. A canyon formed by subaerial erosion and later submergence had a river as its focal mechanism. Some of the submarine valleys south of the Aleutian Islands formed along pre-existing faults (Shepard, 1973). Turbidity currents, known to occur in some active canyons, may initiate canyon formation as well. Currents generated by tides and wind shear have been observed in canyons (Shepard, 1973, 1981) and these may contribute to canyon initiation and formation.

Any listing of the factors which control the formation of submarine canyons likely remains incomplete. Canyons are of composite origin (Shepard, 1981), and a complete list of canyon-forming mechanisms is probably impossible to compile at this time because we have yet to recognize all of the individual factors which contribute to the initiation and excavation of all submarine canyons. Submarine canyons and the conditions under which they form remain, at best, incompletely understood.

The Yoakum canyon is only one of many ancestral submarine canyons to be identified in the subsurface. There are perhaps many more which have yet to be discovered and identified. Because the Yoakum canyon is located in a region of intense hydrocarbon exploration there is a great quantity of data available for its study. As such it provides a unique opportunity for the detailed study of a fossil submarine canyon. I hope that the picture of the Yoakum canyon presented here can be used as a guide for further canyon studies. The Yoakum canyon is in some ways unique and perhaps had a unique set of factors controlling its genesis. How many of these controlling parameters are shared by other canyons cut into clastic, progradational continental margins remains to be seen.

APPENDIX I

Decompaction Methodology

The computer program used in this study was generated specifically for the decompaction of the Yoakum Shale. This program is based on the work of Sclater and Christie (1980).

The following data are required in order to decompact:

1. F_0 = Original surface porosity of the sediments comprising the sedimentary section to be compacted
2. F = Porosity of the sedimentary section at any given depth, Z.
3. $Z_1 - Z_2$ = Thickness of the section to be compacted

Definition of terms:

e	=	2.7183, the exponential function
Z_1	=	present depth to top of sedimentary section
Z_2	=	present depth to bottom of sedimentary section
Z_1'	=	depth to top of decompacted sedimentary section (= 0 because top of decompacted section is at surface)

Z_2' = depth to bottom of decompacted sedimentary layer (= original thickness since $Z_1' = 0$)

c = $-\{\ln(F/Fo)\}/Z$, the slope of the line of porosity decrease with depth when plotted on a semi-log plot. (Fig. 32)

Due to the absence of available porosity and density well logs within the confines of the field area figure 32 was generated using data from the Mississippi Canyon (J. M. Coleman, personal comm.) as well as experimental data derived from the controlled, artificial compaction of shelf mud sediments (W. R. Bryant, personal comm.). This information was plotted and approximated as two curves, with c = 4.2 for depths of less than 262 feet and c = 0.58 for greater depths (Fig. 32).

Additional sedimentary overburden which has been removed by recent erosion is not accounted for in this program.

Sclater and Christie state in appendix A, equation 17 that:

(17) $$Z_2' - Z_1' = (Z_2 - Z_1) - (Fo/c)\{e^{(-cZ_1)} - e^{(-cZ_2)}\} + (Fo/c)\{e^{(-cZ_1')} - e^{(-cZ_2')}\}$$

Since the decompaction of the Yoakum brings the top of the sedimentary section (the Yoakum shale) to the surface than $Z_1' = 0$ and the equation becomes:

(18) $$Z_2' = (Z_2 - Z_1) - (Fo/c)\{e^{(-cZ_1)} - e^{(-cZ_2)}\} + (Fo/c)\{1 - e^{(-cZ_2')}\},$$ or

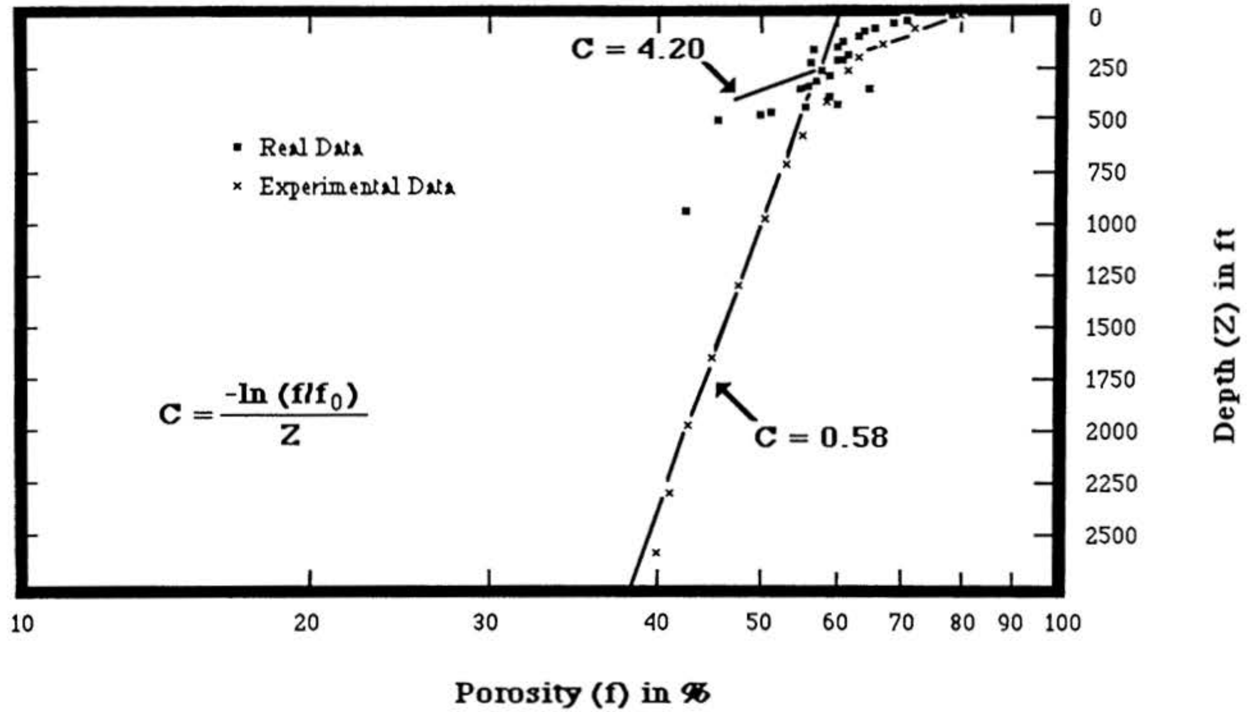


Figure 32: Porosity vs. Depth curves for Yoakum Decompaction Program.

$$(19) \qquad Z_2' + (F_o/c)e^{(-cZ_2')} - (Z_2 - Z_1) - F_o/c + (F_o/c)\{e^{(-cZ_1)} - e^{(-cZ_2)}\} = 0$$

All of the factors in the above expression are known except Z_2', the original thickness of the Yoakum shale. The computer program sets up equation 19 as follows:

$$Z_2' + (F_o/c)e^{(-cZ_2')} = (Z_2 - Z_1) + F_o/c - (F_o/c)\{e^{(-cZ_1)} - e^{(-cZ_2)}\}$$

Originally Z_2' is set equal to $(Z_2 - Z_1)$, the thickness of the Yoakum at depth. This will make the left side of the expression less than the right side and the expression will not balance. The program then increases the value of Z_2' by one foot and tests again for a balanced equation. When the value of the left side of the expression becomes equal to or exceeds the value of the right side then Z_2' has been determined.

The value for c used in the above expression is 0.58; Fo = .60. In order to account for the greater porosities of the sedimentary section above 262 feet (c = 4.2, Fo = .80; Fig. 32) a factor had to be added to the value of Z_2' in order to more closely approximate original thickness. That factor was determined as follows:

Z_2' was determined for both of the two sets of conditions set down by the two curves shown in figure 32:

for Fo = .60, c = 0.58, Z_1 = 131 ft., Z_2 = 393 ft.

and, for Fo = .80, c = 4.20, Z_1 = 131 ft., Z_2 = 393 ft.

Note that Z_1 and Z_2 are the same value for both sets of conditions. Values for Z_1 and Z_2 were chosen so that $(Z_2 - Z_1) = 262$ ft. (the depth to the intersection of the two curves) and in order to bracket the same 262 ft. depth.

For the first set of parameters $Z_2' = 271$ ft. For the second set of parameters $Z_2' = 303$ ft. The difference between these two values is 52 ft. This 52 ft. figure was added to the value of Z_2' as originally determined from equation 19. For sedimentary sections in which the present thickness $(Z_2 - Z_1)$ is less than 52 ft. a proportion of 52 ft. was used.

The actual program, which follows, was designed to run on a Macintiosh 512K computer using MacBasic 2.1.

```
1000 :PRINT:PRINT:PRINT"                    YOAKUM DECOMPACTION
PROGRAM"
'This program is based on the paper "Sclater and Christie: Continental
Stretching-North Sea"
'Journal of Geophysical Research, Vol. 85, No. B7, pages 3711-3739 July 10,
1980'
PRINT:PRINT:PRINT

INPUT "Input Fo (Fo = original surface porosity divided by 100)";Fo
```

```
INPUT "input C (C = -(ln (F/Fo))/z  where F = porosity at depth z (in km))"; c

2000 :
PRINT:INPUT "enter depth to TOP of Yoakum in feet";Z1
INPUT "enter depth to BOTTOM of Yoakum in feet";Z2
depft = Z2-Z1     'original thickness in feet'

Z1 = .0003048*Z1:Z2 = .0003048*Z2  'converts feet to kilometers'

PRINT:PRINT "Just a moment, please.":PRINT

Foc = Fo/c           'for use in following terms'
c = 0-c              'makes c negative'
E1 = EXP(c*Z1)    'for use in following terms'
E2 = EXP (c*Z2)   'for use in following terms'
thick = Z2 - Z1     'for use in following terms'
depth = thick        'sets original thickness to thickness at depth'

a = thick + Foc - Foc*(E1-E2)

'the following loop finds an original depth such that formula (19)'
'in Sclater and Christie's paper = 0'
4000 : b = depth + Foc*EXP(c*depth)
```

```
   IF b >= a THEN GOTO 5000
   depth = depth + .000308    'increases depth by one foot'
GOTO 4000
5000 : depth = depth*3080    'coverts back to feet'
fudge = 52   'feet added to account for non-linear portion at top of porosity/depth plot'
IF depft < 52 THEN fudge = (depft/52)*fudge  'reduces value of fudge for thin layers'

depth = depth + fudge + .5      'adds in fudge factor and readies for reduction from real to integer'

      'The value of fudge (52 feet) was determined using two porosity curves such that:
      'c = 4.20 (Fo = .80) and c = .58 (Fo = .60) and is not accurate for any other situation.
      'These two straight line plots intersected at a depth of 262 feet (80 meters).
      'Fudge was determined as follows: for Fo = .60, c = .58, Z1 = 131, Z2 = 393 then original
      'depth = 271 feet.  For Fo = .80, c = 4.20, Z1 = 131, Z2 = 393 then original depth = 303 feet
      '303 - 271 = 52 = difference in the two computed thicknesses'
```

```
PRINT "original thickness was ";INT(depth);" feet."
meter = depth*.3048:fathom = depth/6
PRINT:PRINT"Or, if you prefer,";INT(.5+meter);"meters or";INT(.5+fathom);"fathoms":PRINT

INPUT "Do you want to run again? (y/n)";y$
IF y$ = "n" THEN  CLS:PRINT:PRINT:PRINT:PRINT"                    Thank you for decompacting with us and have a nice day!":END

c = 0 - c     'makes c positive again'
CLS:GOTO 2000
END
```

APPENDIX II

Cross Section Well Information

CROSS SECTION Y_1-Y_1' West to East

Well No.	Operator	Lease Name
1	Travis Drillers	L. R. Dillon Jr. #1
2	Thomas Schmitz	Lindner #1
3	R. Mosbacher-Carl O&G	Wendt #2
4	Rock Hill Oil Co.., et al	Ray T. Hay #1
5	Rock Hill Oil Co.., et al	Holloway & Mennella #1
6	Sutton Petroleum ltd.	Jim Sherry #1
7	H. C. Starkey	Anderson-Pierce #1

CROSS SECTION Y_2-Y_2' West to East

Well No.	Operator	Lease Name
1	NuCorp Energy	Bruns #1
2	Nat'l Bulk Carriers	Lillian Hinton #1
3	Associated O&G	T. B. Farquhar #1
4	Longhorn O&G	M. G. Johnson #1
5	Texon Roy & Auto Ord.	D. B. Kelley #1
6	Ammex	Cindy B-1
7	Farney and Winn	Kenhard #1
8	Paloma Prod.	Ogston #1
9	W. Earl Rowe	Paul Newton #1

CROSS SECTION Y_3-Y_3' West to East

Well No.	Operator	Lease Name
1	Argo et al	R. M. Granberry #1
2	Lone Star Producing	C. B. McManus #2
3	Fundamental Oil Corp.	J. O. Thigpen #1
4	Catlett and Ferguson	Lampley #1

5	Skelly Oil Co..	N. E. Henderson #1
6	Kirkwood and Morgan	Honish #1
7	H. D. Bruns	A. Honish #1
8	Hugh Goodrich et al	Ist Nichols Nat'l Bank/Kenedy #1
9	Barnsdall Oil Co..	Joe Matula #1

CROSS SECTION C-C' West to East

Well No.	Operator	Lease Name
1	Superior Oil Co.	F. V. Matthew #1
2	Superior Oil Co.	Granberry Oil Unit #1-1
3	Getty Oil Co.	Lillie Melnar #1
4	The Texas Co.	J. Bujnoch #1
5	Mobil Oil Co.	Spanihel #1
6	Bass Enterprises Prod.	J. J. Bender #1
7	Bass Enterprises Prod.	John Lell #1
8	Bass Enterprises Prod.	Mueller #1
9	Trinton O & G Co.	M. Renger #1
10	Bass Enterprises Prod.	Clay Clark #2
11	Lone Star Producing Co.	Albert Sholik #1
12	Superior Oil Co.	Monte Von Rosenberg #1
13	Superior Oil Co.	Monte Von Rosenburg #2
14	Ensearch Exploration	H. A. Pohl #1
15	Howell Drlg. Inc.	Allen G. U. #1
16	H. L. Hawkins	Paul Schulte #1
17	Forest Oil Corp.	H. C. Obelgoner #1
18	Louisiana Nat. Gasoline	HRNCIR #1
19	Howell Drlg. Inc.	Mikeska-Appelt-Woytek #1

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